

Experimental and Clinical Studies
on Volume-Controlled Artificial Ventilation
in Young Individuals

Sten Lindahl

Lund 1977

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STEN LINDAHL

Med.lic., Mlm

Akademisk avhandling
som för avläggande av medicine doktorsexamen
vid Medicinska Fakulteten vid Universitetet i Lund
kommer att offentligen förvaras
å Föreläsningssal 3, Centralblocket, Lasarettet i Lund
torsdagen den 17 november 1977 kl. 09.15

From the Department of Paediatric Surgery (Director: Ass. Prof.
Ludvig Okmian), University Hospital, Lund, Sweden

EXPERIMENTAL AND CLINICAL STUDIES ON
VOLUME-CONTROLLED ARTIFICIAL VENTILATION
IN YOUNG INDIVIDUALS

S T E N L I N D A H L

LUND 1977



This thesis is based on the following papers:

- I. LINDAHL, S. & OKMIAN, L.: Experimental studies on artificial ventilation using the TVM-ventilator. I. Mechanics of ventilation.
- II. LINDAHL, S. & OKMIAN, L.: Experimental studies on artificial ventilation using the TVM-ventilator. II. Dynamics of insufflation.
- III. LINDAHL, S., ARBORELIUS J:r, M. & OKMIAN, L.: Experimental studies on artificial ventilation using the TVM-ventilator. III. Ventilator volume/pressure quotient, pulmonary ventilation, gas distribution, and lung perfusion.
- IV. LINDAHL, S., ARBORELIUS J:r, M. & OKMIAN, L.: Experimental studies on artificial ventilation using the TVM-ventilator. IV. Duration of inspiration, pulmonary ventilation, gas distribution, and lung perfusion.
- V. LINDAHL, S., ARBORELIUS J:r, M. & OKMIAN, L.: Experimental studies on artificial ventilation using the TVM-ventilator. V. Ventilatory frequency, pulmonary ventilation, gas distribution and lung perfusion.
- VI. LINDAHL, S., KUGELBERG, J. & OKMIAN, L.: Experimental studies on artificial ventilation using the TVM-ventilator. VI. The circulatory response to specific ventilatory patterns.
- VII. LINDAHL, S., OKMIAN, L. & THOMSON, D.: Artificial ventilation in children during anaesthesia using the TVM-ventilator. Standards for ventilation, and ventilatory patterns at frequencies of 15 and 20.

Reference to these papers will be made by the numerals I - VII.

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INTRODUCTION

In volume controlled artificial ventilation, the setting of the respiratory gas volume and frequency is the primary measure, and it is these two factors that determine the end-inspiratory tracheal pressure level under prevailing pulmonary conditions.

In adults, volume controlled artificial ventilation has for decades been the method of choice compared to pressure controlled ventilation.

The majority of volume controlled ventilators, however, have been designed for the large ventilatory volumes of the adult patient. To effectuate the diminutive ventilatory volumes of a neonatal infant only a minor output of force is required by the ventilator. MUSHIN et al 1962 and MATTILA 1974 claimed that during such conditions the power available to overcome the high resistance of the infant airway and narrow tracheal tubes is insufficient. Thus pressure controlled ventilation is still frequently used in infants during surgery and pre- and postoperative intensive care.

It is well known that steady state artificial ventilation of infants does not exist except for short periods. Even during anaesthesia and muscle relaxation, significant changes of total compliance occur instantly as the result of surgical manipulations (OKMIAN et al 1966). One serious disadvantage of pressure controlled artificial ventilation is that changes in ventilatory conditions cannot be detected. Consequently, adjustment of the ventilatory settings to satisfy changed pulmonary mechanical conditions is impossible without laboratory samples and time delay.

Most volume controlled ventilators are constructed for setting of the minute volume. This means that the amount of compressed gas within the ventilator and its tubing has to be calculated and deduced in order to estimate the actual pulmonary ventilation. The minute volume setting procedure also implies that the tidal volume is dependent upon the choice of frequency. Consequently tidal volume increases or decreases when the ventilatory frequency is altered.

The monitoring of pulmonary ventilation breath by breath offers the best possibilities for close and continuous control of the respiratory volume and the mechanics of ventilation. A new device for artificial ventilation, the TVM-ventilator (Tidal Volume Monitoring, OKMIAN 1973, OKMIAN et al 1974) fulfils these requirements. According to criteria set by MUSHIN et al (1969) this ventilator can be characterized as a volume controlled, time cycled ventilator with a rapid decelerated insufflation of the tidal volume.

The tidal volume and end-inspiratory tracheal pressure levels are also of significant importance for the venous return, cardiac output and pulmonary and systemic circulation during artificial ventilation, previously investigated by several authors, whose studies have mainly been concerned with the interaction of these factors and pulmonary ventilation (WERKÖ 1947, COURNAND et al 1948, NORLANDER 1968, NORDSTRÖM 1972, JOHANSSON 1975, LUNN et al 1975). The advantages and disadvantages of ventilatory parameters such as flow pattern, tracheal pressure profile, dynamic course of insufflation, pressure or volume controlled ventilation, end-inspiratory tracheal plateau phase and magnitude of ventilatory frequency are still under debate, mainly because of the contrasting relationship between optimal pulmonary ventilation and blood circulation (BERGMAN 1967, BAKER 1971, JONZON et al 1971, JOHANSSON & LÖFSTRÖM 1975).

This series of experiments was planned in order to gain more substantial knowledge of pulmonary ventilation, gas distribution and gas exchange as well as of the haemodynamic conditions at different ventilatory settings and in order to outline standards for safe and efficient mechanical ventilation of neonates and children without seriously embarrassing the blood circulation.

PURPOSE OF THE STUDY

The experimental investigations were designed to study:

- the accuracy of tidal volume setting
- the dynamic course of insufflation
- the ventilator volume/pressure quotient
- simulated pressure-controlled and volume-controlled artificial ventilation
- low and high ventilatory frequencies

The clinical investigation was designed with a view to finding appropriate standards for the ventilatory volume setting in neonates and small infants during anaesthesia and surgery.

MATERIAL

The experimental series (I-VI) included 41 piglets of the Swedish native breed with body weights between 2.7 and 24.5 kg. These animals were investigated on 53 occasions.

Table 1. Number of piglets and examinations per piglet. Animals no. 25-41 were only used once (investigation no. VI).

Piglet		I	II	III	IV	V	VI
No.							
1.		++	+				
2.		++	++				
3.		+	+				
4.		++	++				
5.		+	+				
6.		+	+				
7.		++++++	++++++				
8.		+++++	+++++				
9.			+		+	+	
10.			+		+	+	
11.			+			+	
12.			+		+		
13.			+			+	
14.			+			+	
15.			+				
16.			+	+			
17.			+	+			
18.			+	+			
19.			+	+			
20.			+	+			
21.			+		+		
22.			+		+		
23.			+		+		
24.			+				
25-41.							+

The clinical series (VII) enclosed 16 children with healthy lungs and body weights between 2.6 and 22.6 kg. All investigations were performed during abdominal procedures.

SYMBOLS AND CALCULATIONS

b.w.	Body weight, (kg)
C_L	Lung compliance, (ml/kPa)
C_{THX}	Thoracic compliance, (ml/kPa)
C_{TOT}	Total compliance, (ml/kPa)
C_{vent}	Ventilator volume/pressure quotient, (ml/kPa)
f	Ventilatory frequency, (cycles/minute)
h.r.	Heart rate, (beats/minute)
FiO_2	Inspired oxygen fraction
LA	Left pulmonary apex
LB	Left pulmonary base
ΔP	Instantaneous pressure change (kPa)
$P_{A-a}O_2$	Alveolo-arterial oxygen difference, (kPa)
P_aCO_2	Arterial carbon dioxide tension, (kPa)
P_{Ao}	Aortic pressure, (kPa)
P_aO_2	Arterial oxygen tension, (kPa)
P_{AP}	Pulmonary arterial pressure, (kPa)
P_B	Atmospheric pressure, (kPa)
PC	Ventilator pressure chamber
PCW	Pulmonary capillary wedge pressure, (kPa)
$\bar{P}_E CO_2$	Mean partial pressure of carbon dioxide in mixed expired gas, (kPa)
P_{ei}	End-inspiratory tracheal pressure, (kPa)
$P_{ET} CO_2$	End-tidal carbon dioxide tension, (kPa)
$P_I CO_2$	Partial pressure of carbon dioxide in inspired air, (kPa)
P_{la}	Left atrial pressure, (kPa)
P_{peak}	Tracheal peak pressure, (kPa)
P_{pl}	Pleural pressure, (kPa)
P_{ra}	Right atrial pressure, (kPa)
P_{vent}	Pressure in the ventilator pressure chamber, (kPa)
PVR	Pulmonary vascular resistance, (units)
$\dot{Q}$	Cardiac output, (l/min)
Qr	Regional pulmonary perfusion (percentage of total pulmonary perfusion)
RA	Right pulmonary apex
RB	Right pulmonary base
RQ	Respiratory quotient
SPCV	Simulated Pressure Controlled Ventilation

SV	Stroke volume, (ml)
SWL	Stroke work left ventricle, (Nm)
SVR	Systemic vascular resistance, (units)
SWR	Stroke work right ventricle, (Nm)
Δt	Inspiration/unit time, (s)
t_{exsuff}	Exsufflation time, (s)
t_{insuff}	Insufflation time, (s)
t_{pl}	Duration of rising pleural pressure, (s)
TVM	Tidal Volume Monitoring
ΔV	Instantaneous gas amount change, (ml)
$\dot{V}_A$	Alveolar ventilation, BTPS, (ml)
$\dot{V}_A$	Alveolar minute ventilation, BTPS, (l/min)
$\dot{V}_{\text{CO}_2}$	Carbon dioxide production, STPD, (ml/min)
VCV	Volume Controlled Ventilation
V_{Dalv}	Alveolar dead space, (ml)
V_{Danat}	Anatomical dead space, (ml)
V_{Dc}	External dead space (compressed gas in tubing), (ml)
V_{Dphys}	Physiological dead space, (ml)
$\dot{V}_E$	Expired minute ventilation, BTPS, (l/min)
$\dot{V}_{\text{O}_2}$	Oxygen consumption, STPD, (ml/min)
Vr	Regional pulmonary ventilation (percentage of total pulmonary ventilation)
V_{Tc}	Compressed gas in tubing, (ml)
$V_{\text{Tgas meter}}$	The volume of a single breath in ml, calculated from the expired minute volume measured by gas meter
V_{Texp}	Tidal volume, BTPS, (ml)
V_{Tvent}	Tidal volume, read on the ventilator's dial, (ml)
V_{Tpat}	Calculated tidal volume, (ml) ($V_{\text{Tpat}} = V_{\text{Tvent}} - V_{\text{Tc}}$)

$$C_{\text{TOT}} = \frac{V_{\text{Tvent}}}{P_{\text{ei}}} ; C_{\text{TOT}} = \frac{V_{\text{Texp}}}{P_{\text{ei}}} ; C_{\text{TOT}} = \frac{V_{\text{Tpat}}}{P_{\text{ei}}} ;$$

$$C_L = \frac{V_{\text{Tvent}}}{P_{\text{ei}} - P_{\text{pl}}} ; \frac{1}{C_{\text{TOT}}} = \frac{1}{C_L} + \frac{1}{C_{\text{THX}}} ;$$

$$RQ = \frac{\dot{V}_{CO_2}}{\dot{V}_{O_2}} ;$$

$$V_{D_{phys}} = \frac{P_{aCO_2} - \bar{P}_{ECO_2}}{P_{aCO_2} - P_{ICO_2}} \times V_{T_{exp}} ;$$

$$V_{D_{anat}} = \frac{P_{ETCO_2} - \bar{P}_{ECO_2}}{P_{ETCO_2} - P_{ICO_2}} \times V_{T_{exp}} - V_{D_c} ;$$

$$V_{D_{alv}} = V_{D_{phys}} - V_{D_{anat}} ;$$

$$V_A = V_{T_{exp}} - V_{D_{phys}}$$

$$PVR = \frac{P_{AP} - P_{la}}{\dot{Q}} ; \quad SVR = \frac{P_{Ao} - P_{ra}}{\dot{Q}} ;$$

$$SWR = SV (P_{AP} - P_{ra}) ; \quad SWL = SV (P_{Ao} - P_{la})$$

Current statistical methods for mean values, standard deviation and standard error of the mean were used. Evaluation of the results was performed using paired significance tests according to Student's t-test (* = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$).

THE VENTILATOR

The construction of the TVM-ventilator * (Tidal Volume Monitoring, OKMIAN 1973) is intimately connected with the principle used for tidal volume estimation (2-pressure method, OKMIAN 1963).

The ventilator consists of a rigid-walled pressure chamber (PC), valves and an electronic module (EM) (Fig. 1). During expiration a certain amount of gas enters PC, through the filling valve (1) until a certain pressure is reached. The closure of the valve is directed electronically. After a set period, the expiratory valve (3) is closed and the inspiratory valve (2) opens. Pressure equalization occurs within the system-PC, tubing, airways and lungs (i.e. insufflation). The pressure drop (P_{diff}) within PC during the equalibration procedure is proportional to the volume of gas (V_{Tvent}) that leaves PC and can be expressed by the formula:

$$V_{Tvent} = P_{diff} \cdot \text{const.} \quad (2\text{-pressure method})$$

The value of the constant depends upon the volume of PC. The differential manometer (M) directs valve 1 and records the pressure drop during inspiration.

A characteristic feature of the working mechanism of the ventilator is that the surplus volume of compressed gas is retained within PC during inspiration. The end-inspiratory pressure is maintained in the PC during expiration. The tidal volume is set breath by breath and read on a dial. The tidal volume setting is independent of the ventilatory frequency setting. Accordingly gas transport and mechanics of ventilation are separate setting procedures

*Manufactured by Micatrone Regulator Ltd, Stockholm, Sweden

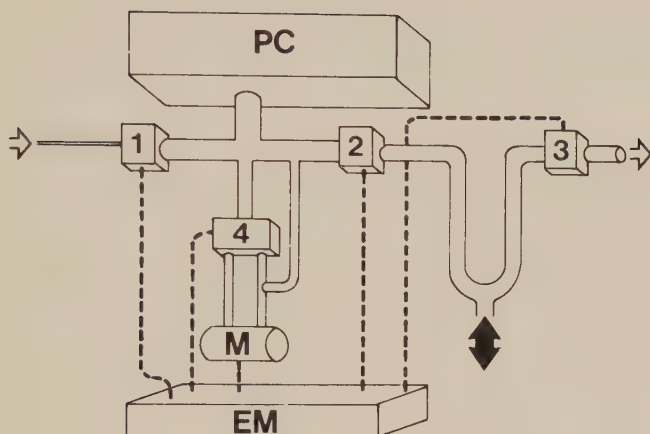


Fig. 1. Schematic representation of the TVM-ventilator.

Open arrows denote gas inlet and outlet. Filled arrow the tracheal connection.

1 - 4 electromagnetic valves

PC pressure chamber

EM electronic module

M differential electromanometer

METHODS

Anaesthesia

The animals were fasted for at least four hours before examination (I-VI). A combination of Dridol (Droperidolum INN) 1 - 2 mg/kg b. w. and Ketalar (Ketaminum NFN) 30 - 50 mg/kg b. w. was injected intramuscularly. The piglets were intubated with a cuffed oro-tracheal tube and ventilated with room air. Alloferin (Alcuronium NFN) 1 - 2 mg was used intravenously for muscle relaxation when needed.

In the clinical investigation (VII) anaesthesia was induced by inhalation of Fluothane (Halothane, NFN) in combination with oxygen and nitrous oxide. Celocurin (Suxamethonium, NFN) was used for intubation. After the patient had been intubated, balanced anaesthesia (Pethidin, N_2O/O_2) with Pavulon (Pancuronum, INN) for muscle relaxation, was used.

Airway obstruction

Regional bronchial airway obstruction was obtained by inserting a metal cylinder (ID = 1 mm) in the right caudal lobe bronchus (III-V).

Pulmonary ventilation

Tidal volume, read on the dial of the ventilator (V_{Tvent}) was used for volume control of ventilation in all investigations. Correction for compressed gas volume in the tubing (V_{TC}) was performed in the clinical study (VII).

The accuracy of the tidal volume setting was determined by comparison with expired 5 minute gas volume samples read on a gas meter (I). The expired breathing gas was also sampled in Douglas bags, for 10 minute periods, and analysed according to Scholander (1947). During the 10 minute periods arterial blood samples were withdrawn and CO_2 as well as O_2 tensions were estimated by conventional techniques (III).

The setting of V_{Tvent} (III-VII) was monitored during the examinations by simultaneous analyses of the end-tidal CO_2 fraction by means of an infra-red CO_2 meter. The value of the end-tidal CO_2 fraction analyses was checked by comparison with the corresponding arterial CO_2 tensions.

Mechanics of ventilation

Total compliance was used as a criterion of prevailing respiratory conditions (I-VII). In addition, lung and thoracic compliance were calculated (VI).

Dynamics of insufflation

Reverse plethysmography was used for recording the dynamic course of insufflation, using the ventilator's pressure chamber as a plethysmograph. On inspiration the pressure in the ventilator's pressure chamber decreased in proportion to the amount of gas that left the ventilator. The correlation between 0.1 s tidal volume changes and the corresponding changes in tracheal pressures was used to describe the dynamic course of insufflation (II).

Gas distribution and lung perfusion

Xe¹³³ radiospirometry was employed for the determination of gas distribution and lung perfusion (III-V). The equipment and technique have previously been described by MIÖRNER (1968) and ARBORELIUS et al (1970). Four symmetric pulmonary fields were available for analyses.

The animals to be examined were placed horizontally on their backs, fixed on a pillow filled with plastic balls. When the gas in the pillow was evacuated the pillow assumed a firm consistency. Through light sources on the detectors luminous spots were marked out on the animals so that the initial position, if changed during examination, could be exactly reproduced.

Rebreathing of Xe^{133} was not performed. Thus, the results show relative changes in gas distribution and lung perfusion.

Circulation

In 19 out of 20 investigations cardiac output was estimated by the electromagnetic flow meter technique (Nycotron 372). This procedure included sternotomy. The electromagnetic probe encircled the main stem of the pulmonary artery. The two atria, the pulmonary artery and the aorta were catheterised with end-hole catheters (PE 160).

In one instance the cardiac output was determined by the thermodilution technique (Swan-Ganz, 7 F, Edwards Lab. USA). Isotone saline (temperature $0 - +1^{\circ}\text{C}$) was injected into the right atrium. P_{AP} and PCW pressures were registered from the tip of the catheter. The thermistor was connected to a digital computer (Model 9600, Cardiac output computer, Edwards Lab. USA).

Pressure recordings

Electromanometry was used in all investigations (I-VII, Siemens-Elema, EMT 34, EM 41 and 81). In one of the investigations, (VI) simultaneous registration from two synchronized recorders was required.

Calibration

The electromanometers for airway pressures (P_{vent} , P_{peak} , P_{ei} and P_{pl}) were calibrated by means of a water column (I-VI) and a mercury manometer (VII).

The electromanometers for circulatory pressure measurements (P_{ra} , P_{AP} , P_{la} and P_{AO}) were calibrated to a column of water corresponding to 100 mm of mercury (VI).

RESULTS

Experimental investigations

Accuracy of tidal volume setting

In 6 piglets with body weights between 2.6 and 24.5 kg, 170 measurements of different tidal volumes, set on the ventilator, were correlated to expired 5 minute volumes registered on a dry gas meter. The average value $V_{T_{vent}}/V_{T_{gas\ meter}}$ was 1.06 ± 0.027 i.e. the percentage difference between set and measured tidal volume was $6.0 \pm 2.7\%$ without correction to BTPS (I).

The percentage difference for mean values ($n = 5$) of $V_{T_{vent}}$ and $V_{T_{exp}}$ calculated from expired 10 minute volumes corrected to BTPS was 2.3% with a ventilator volume/pressure quotient of 20 ml/kPa and 1.6% with a C_{vent} of 80 ml/kPa when ventilating un-obstructed airways (III).

Dynamics of insufflation

During insufflation a rectilinear relationship was found to exist between ΔV and ΔP .

The rectilinear relationship was not influenced either by the body size of the subject, total compliance or tidal volume.

C_{vent} did, however, significantly influence P_{peak} and the size of the coefficient $\Delta V/\Delta P$ as well as the t_{insuff} .

A low C_{vent} resulted in a high P_{peak} and a short t_{insuff} and vice versa.

Ventilator volume/pressure quotient

A C_{vent} of 20 ml/kPa represented a more energetic ventilation than that of 80 ml/kPa. The most obvious effect of the power increase was the decrease in inspiration time.

C_{TOT} was not influenced by C_{vent} (III), but when the animals were sternotomized a significant decrease in C_{TOT} and C_L appeared (VI).

With un-obstructed airways there was no significant difference in arterial blood gases, $V_{D_{phys}}/V_{T_{exp}}$ ratio, V_A , RQ, gas distribution or lung perfusion between ventilation with $C_{vent} 20$ and $C_{vent} 80$ (III).

With bronchial obstruction and $C_{vent} 20$ the estimated values for V_A , RQ and P_{aO_2} were greater in proportion to $C_{vent} 80$ ml/kPa, while lung perfusion was unchanged (III).

Bronchial obstruction reduced the gas distribution to the obstructed area by 24.1% when $C_{vent} 20$ was used and by 21.9% for $C_{vent} 80$ ml/kPa (n.s.).

In the un-obstructed lung bases the ventilation was reduced by 14.9% with a C_{vent} of 20, while there was an increase of 8.3% with a C_{vent} of 80 ml/kPa.

The decrease in ventilation of the lung bases with $C_{vent} 20$ was compensated for by a large increase in ventilation within the apical areas of the lungs, while gas distribution within the un-obstructed areas was more evenly distributed with $C_{vent} 80$. Pulmonary ventilation was maintained at the same value with regional bronchial airway obstruction mainly through hyper-expansion of the un-obstructed lung areas (III).

The results showed that the insufflation time during artificial ventilation reflects the ventilator's efficiency. When the ventilator's efficiency is defined, measurement of the duration of insufflation enables evaluation of the prevailing conditions within the lungs. Ventilation at a volume/pressure quotient 20 ml/kPa followed by a high endotracheal peak pressure showed no essential advantages compared with a volume/pressure quotient 80 ml/kPa and a low endotracheal peak pressure.

SPCV and VCV

When equal tidal volumes were administered by SPCV and VCV-ventilation a higher P_{peak} and P_{ei} and a lower C_{TOT} were demonstrated to occur with SPCV, compared to those with VCV.

SPCV in regional bronchial airway obstruction, showed reduced values of V_A and $V_{\text{D}_{\text{anat}}}$ while the $V_{\text{D}_{\text{phys}}}/V_{\text{Texp}}$ ratio increased in proportion to VCV.

SPCV ventilated the apical pulmonary fields sufficiently while the right caudal field was poorly ventilated probably due to abdominal inertia (IV).

Low and high ventilatory frequencies

Normoventilation at the ventilatory frequency of 10.3 cycles/minute required tidal volumes twice as large as those with ventilation at 30 cycles/minute. The corresponding P_{ei} was 1.7 and 0.76 kPa. Our results revealed that in species whose normal spontaneous breathing frequency is high normoventilation at low ventilatory frequencies could be obtained without reaching dangerous end-inspiratory tracheal pressure levels, even when regional bronchial obstruction was induced.

The $V_{\text{D}_{\text{phys}}}/V_{\text{Texp}}$ ratio was greater at $f = 30$ than at $f = 10.3$. This could be related to a significant increase in the $V_{\text{D}_{\text{anat}}}/V_{\text{Texp}}$ ratio at $f = 30$, while the $V_{\text{D}_C}/V_{\text{Texp}}$ and $V_{\text{D}_{\text{alv}}}/V_{\text{Texp}}$ were unchanged at both frequencies. The increased amount of gas required to ventilate the non- CO_2 producing parts of the ventilatory system (animal + tubing) at $f = 30$, was thus mostly due to an increased anatomical dead-space ventilation. A large proportion of the respiratory cycle was wasted due to dead-space ventilation at the higher frequency. One cycle at $f = 30$ demanded 70 - 75% of the time required for the transport of the larger tidal volume at $f = 10.3$ cycles/minute (V).

With un-obstructed airways, four-field radiospirometry revealed even gas distribution and lung perfusion at both frequencies. With

regional bronchial obstruction and $f = 30$ the ventilation and perfusion within the obstructive pulmonary field was reduced to some extent in proportion to the corresponding values at $f = 10.3$ cycles/minute. This could be explained by air trapping (V).

Paradoxically, the exsufflation time with regional bronchial obstruction was shorter in proportion to the exsufflation time with an unobstructed airway at both frequencies. The time reduction could probably be related to the prevailing hyperventilation of the unobstructed lung compartments and accordingly increased P_{ei} and pressure gradient for exsufflation in these areas.

Higher $\dot{Q}$, lower PVR and SVR were demonstrated at $f = 11$ (inspiration time 20%) compared to those at $f = 30$ (inspiration time 50%) (VI).

An increase of inspiration time by about 100% at the lower ventilatory frequency ($f = 11$) resulted in a moderately increased work load for the right heart, which was also reflected by a small decrease in cardiac output (7%) (VI).

The corresponding measurements at the higher ventilatory frequency ($f = 30$) resulted in a significant but uncompensated decrease in cardiac output and stroke volume (VI).

Clinical investigation

Ventilatory standards in children during anaesthesia and surgery

A rectilinear relationship was established between C_{TOT} and kg b.w. at ventilatory frequencies of 15 and 20 cycles/minute. The regression equation at $f = 20$ cycles/minute was $C_{TOT} = 11.2 \cdot \text{kg b.w.} - 12.5$. The coefficient of correlation was 0.95.

C_{TOT} measured after intubation but before surgery was 143.5 ± 21.3 ml/kPa. C_{TOT} decreased significantly to 122.5 ± 18.1 ml/kPa during the initial stages of the surgical procedure. Total compliance remained unchanged when the ventilatory frequency was reduced from 20 to 15 cycles/minute (VII).

V_{Tpat} was linearly correlated to kg b.w. at a ventilatory frequency of 15 as well as at 20 cycles/minute during slight hyperventilation (P_aCO_2 3.9 ± 0.11 kPa and 3.7 ± 0.14 kPa, respectively) (VII).

At 15 cycles/minute the regression equation was $V_{Tpat} = 14.6 \cdot \text{kg b.w.} + 16$, coefficient of correlation was 0.97. Mean values and standard deviation of tidal volume were 15.9 ± 1.5 ml/kg b.w. and corresponding P_{ei} were 1.6 ± 0.07 kPa (VII).

At 20 cycles/minute the regression equation was $V_{Tpat} = 12.3 \cdot \text{kg b.w.} - 2.1$. Coefficient of correlation was 0.99. The mean values and standard deviation of tidal volume were 12.1 ± 1.4 ml/kg b.w. and corresponding P_{ei} were 1.3 ± 0.06 kPa.

In order to deliver an adequate V_{Tpat} to the older children P_{vent} was substantially increased at both frequencies. However, the increased pressure of P_{vent} did not influence the pressure level of P_{peak} and P_{ei} . This could be explained by the hypothesis that the proportional increase in lung volume and functional residual capacity in the older children compensated for the higher pressures within the ventilator pressure chamber when large tidal volumes were administered.

GENERAL DISCUSSION

The piglet was chosen as the experimental animal because of its close physiological relationship to humans, the similarity of body size, the fast growth rate and our long experience of anaesthetising and breeding the animal (DYRENDAHL et al 1953, BUSTAD 1966, KORNFÄLT 1973). It is obvious that quantitative experimental data cannot be directly conclusive for human conditions, but qualitative changes during comparative experimental conditions are often relevant. In all our investigations the first recordings were used as reference for the later measurements throughout the examinations.

The piglet's suitability as experimental animal was supported by the results in paper no. I. In both piglets and children a linear relationship existed during anaesthesia between total compliance and kg b.w. (I, VII). Total compliance was somewhat higher in the piglet than in the child, but different anaesthetic agents and positioning were used and in the experimental studies no correction of tidal volume was made for the gas volume compressed in the tubing.

Accuracy of tidal volume setting

The percentage difference between $V_{T_{vent}}$ and $V_{T_{gas\ meter}}$, i.e. set and registered tidal volume, was $6.0 \pm 2.7\%$. This error was probably to a large extent due to a systematical deviation because of the calibration of the ventilator prototype used, and also to some extent a consequence of the fact that no correction of the expired gas volumes to BTPS was made (I). In our opinion this precision in the tidal volume setting is sufficient even for the preterm neonatal baby. In a later investigation a higher accuracy in tidal volume setting was shown (2.3% deviation), when the fully developed ventilator model was used and the expired gas volumes were corrected to BTPS (III).

Dynamic course of insufflation

The existence of a rectilinear relationship between ΔV and ΔP during the decelerating phase of the insufflation made possible a prospective estimation of the dynamic course of insufflation, probably of prognostic significance. This rectilinear relationship existed irrespective of body size, total compliance and magnitude of tidal volume. Thus the $\Delta V/\Delta P$ value for piglets and children during comparable C_{vent} may indicate specificity to different species. In small individuals the main part of lung excursion appears in the abdominal direction. It may be supposed that the visceral abdominal mass probably influences the $\Delta V/\Delta P$ ratio.

Ventilator volume/pressure quotient

Duration of insufflation and gas distribution were influenced by the C_{vent} setting. A low C_{vent} implied that the tidal volume was compressed within a small PC to a high pressure level. Consequently, the available energy for lung expansion was large. The increased efficiency of the ventilator was primarily reflected in a shorter duration of insufflation. With a C_{vent} of 80 ml/kPa the duration of insufflation was approximately 40% and with a C_{vent} of 20 approximately 30% of the time required for respirators using accelerated inspiratory gas flow (OKMIAN et al 1974). The gain in time enables the use of high ventilatory frequencies (II, III). The short insufflation time also allows an increase in expiration time to the benefit of lung perfusion (V, VI).

After thoracotomy, the values of C_{TOT} and C_L were lower with a C_{vent} of 20 in proportion to the corresponding values with a C_{vent} of 80 ml/kPa (VI). On the other hand, no difference in C_{TOT} was measured when these volume/pressure quotients were used in piglets not subjected to thoracotomy (III).

Four-field Xe^{133} -radiospirometry further explained these differences (III). With a C_{vent} of 20 ml/kPa and regional obstruction of the right caudal lobe bronchus, the cranial pulmonary field was

over-ventilated, while a C_{vent} of 80 ml/kPa resulted in an even gas distribution within un-obstructed pulmonary fields. After thoracotomy, mechanically affected pulmonary regions probably gave rise to locally prolonged time constants and reduction of total compliance.

From a clinical point of view the low C_{vent} setting may only be of advantage when extremely low compliant lungs have to be ventilated at ventilatory frequencies of over 50 cycles/minute.

SPCV and VCV

SPCV was achieved by shortening the inspiration time to 10% of the breathing cycle. This meant that the insufflation was interrupted during lung expansion. With pressure-controlled artificial ventilation momentary changes in total compliance were not recorded and thus the pulmonary ventilation was reduced with consequent risk of hypoventilation (IV).

In addition to these disadvantages it was demonstrated that P_{peak} and P_{ei} were higher with SPCV than with VCV when volumes of equal size were administered (IV). Ventilation of the obstructed lung field was reduced to a larger extent with SPCV than with VCV and the gas distribution to the un-obstructed fields more uneven with SPCV. These draw-backs could mainly be explained by the pressure profile used with SPCV (IV). It is true that SPCV in combination with time cycling devices avoids the disadvantages reported here, but even if these respiratory mechanical properties were fulfilled the loss of control of the volume of ventilation with SPCV is unacceptable.

Low and high ventilatory frequencies

High ventilatory frequencies can be hazardous for the lungs when the expiratory phase is too short to allow low compliant pulmonary compartments to terminate their expiration. Such conditions may result in air trapping (V). When equal inspiration times were used

(1 s/breathing cycle) the size of Q, PVR and SVR were equivalent or even advantageous at the lower of the two ventilatory frequencies tested ($f = 11$ and $f = 30$, VI). When the inspiration time at $f = 11$ was prolonged from 1 s to 2.7 s, the corresponding cardiac output was only slightly decreased in spite of the fact that the pulmonary vascular resistance increased by 223%. This could be explained by the significant increase in the stroke work of the right ventricle. Shortening of the expiration time during these conditions was deleterious to the circulation and clearly demonstrated the importance of a long expiration to the benefit of the pulmonary circulation (VI).

It may be stated that the size of the endotracheal pressure obtained at ventilatory frequencies within the range 10 - 30 cycles/minute is of minor importance during normoventilation of individuals with healthy lungs and normal heart function.

On the other hand the duration of positive pressure in the lungs or the number of cardiac systoles per minute influenced by the endotracheal pressure during artificial ventilation, are of the utmost importance.

Ventilatory standards in children during anaesthesia and surgery

Artificial ventilation in children during anaesthesia or pre- and postoperative treatment, demands immediate and adequate setting of the pulmonary ventilation. The clinical investigation (VII) produced standards for a primary setting to fulfil these conditions. In addition, the prevailing pulmonary mechanical conditions were outlined. However, during prolonged anaesthesia and ventilator treatment, for instance postoperatively, the pulmonary setting had to be checked regularly by blood gas analyses.

Two ventilatory frequencies were chosen, $f = 15$ and $f = 20$. The lower ventilatory frequency because of the results in the experimental studies, and $f = 20$ cycles/minute because of its frequent use in clinical practice and for comparison with previously reported standards (ENGSTRÖM et al 1962 and OKMIAN 1963).

Prerequisite conditions for normoventilation at the two ventilatory frequencies were a pulmonary ventilation adjusted to give slight hyperventilation corresponding to a $P_{ET}CO_2$ of 4 kPa. According to arterial control analyses P_aCO_2 was at $f = 15$ within 3.9 ± 0.11 kPa and at $f = 20$ within 3.7 ± 0.14 kPa.

A rectilinear relationship between $V_{T_{pat}}$ and kg b.w. was shown at the two ventilatory frequencies. The regression equation at $f = 20$ cycles/minute showed an approximately direct proportionality expressed by the equation $V_{T_{pat}} = 12.3 \cdot \text{kg b.w.} - 2.1$. The mean value for $f = 20$ cycles/minute was 12.1 ± 1.4 ml/kg b.w. Thus tidal volumes of 12 ml/kg b.w. at $f = 20$ cycles/minute can be recommended.

The estimation of $V_{T_{pat}}$ at $f = 20$ cycles/minute from the regression equation and the mean value resulted in divergencies of 4% for a child of 3 kg and of 1% for a child of 20 kg b.w. Compared to previously reported standards (RADFORD et al 1954, RADFORD 1955, ENGSTRÖM et al 1962 and OKMIAN 1963) our values are higher. These differences were comprehensively discussed in paper no. VII.

The regression equation at $f = 15$ cycles/minute was $V_{T_{pat}} = 14.6 \cdot \text{kg b.w.} + 16$. The mean value for $V_{T_{pat}}$ at 15 cycles/minute was 15.9 ± 1.5 ml/kg b.w. The tidal volume calculated from the mean value for a child of 3 kg b.w. was 20% lower than the value calculated from the regression equation, and that for a child of 20 kg was over-estimated by 3% in proportion to the values calculated from the regression equation. Thus calculations of $V_{T_{pat}}$ for $f = 15$ cycles/minute from the mean value differed greatly, especially in the case of small children. Thorough determinations demand the use of the regression equation as a formula at $f = 15$ cycles/minute.

GENERAL SUMMARY

The experimental series included 41 piglets between 2.7 and 24.5 kg b.w. In 92 examinations on 8 animals, $C_{TOT}/\text{kg b.w.}$ was found to be $15.4 \pm 5.0 \text{ ml/kPa/kg}$, which was somewhat higher than that in infants (I). The piglet was shown to be a suitable animal for studies on pulmonary and circulatory response during artificial ventilation.

The accuracy of respiratory volumes was studied under anaesthesia and controlled ventilation in 170 examinations in 8 animals (I). The error between set and registered tidal volume was found to be $6.0 \pm 2.7\%$.

The dynamic course of insufflation was investigated in 23 piglets. A rectilinear relationship between the instantaneous amount of breathing gas delivered and the corresponding pressure in the airways was found during insufflation. The rectilinear relationship was not influenced by body size, total compliance or tidal volume. However, the ventilator's volume/pressure characteristics significantly influenced the size of the tracheal peak pressure and the size of the direction coefficient for the linear dynamic volume/pressure relation during insufflation, as well as the duration of the insufflation. A low ventilator volume/pressure quotient resulted in increased work to overcome airway resistance.

The influence of the ventilator/pressure quotient on pulmonary ventilation and circulation was studied in 12 piglets. Following regional bronchial obstruction V_A , RQ and P_aO_2 were greater with a low ventilator volume/pressure quotient ($C_{vent} 20 \text{ ml/kPa}$) than with a high ($C_{vent} 80 \text{ ml/kPa}$). Total compliance was unchanged. However, C_{TOT} and C_L following thoracotomy decreased with a C_{vent} of 20 compared to those with a C_{vent} of 80 ml/kPa. With four-field radiospirometry a more even gas distribution was shown to exist with a C_{vent} of 80 compared to that with a C_{vent} of 20 ml/kPa. Ventilation with a low C_{vent} and a high endotracheal peak pressure showed no essential advantages over a high C_{vent} and a low endotracheal peak pressure.

In 6 animals ventilatory data from simulated pressure controlled ventilation and volume controlled ventilation were compared. During SPCV (10% inspiration time) higher P_{peak} and P_{ei} were required than during VCV (33% inspiration time).

With SPCV the cranial pulmonary fields were better ventilated, while the right caudal field was less well ventilated due to abdominal inertia.

With SPCV and regional bronchial airway obstruction, V_A and $V_{D_{\text{anat}}}$ were reduced, while the $V_{D_{\text{phys}}}/V_{T_{\text{exp}}}$ ratio was increased in comparison with volume controlled ventilation. As steady-state artificial ventilation hardly exists except for short periods, especially in neonates, volumetrical control of pulmonary ventilation is to be preferred.

Normoventilation at two ventilatory frequencies, 10 and 30 cycles/minute was established in 14 piglets.

In- and exsufflation of tidal volumes at $f = 30$ cycles per minute demanded 70 - 75% of the time required for the transport of tidal volumes twice as large at $f = 10.3$. A large proportion of the respiratory cycle was wasted due to anatomical dead-space ventilation at the higher ventilatory frequency. Higher $\dot{Q}$, lower PVR and SVR were measured at $f = 11$ (inspiration 20%) compared to the same values at $f = 30$ (inspiration 50%). An increase of inspiration time by about 100% at the lower ventilatory frequency ($f = 11$) resulted in a moderately increased work load for the right heart, which was also reflected by small decreases in cardiac output and stroke volume. These results demonstrated the advantage of a rapid insufflation in order to give longer expiration time per minute to the benefit of the venous return and cardiac output.

The clinical series used for producing ventilatory standards comprised 16 children with healthy lungs and body weights between 2.6 and 22.6 kg. All investigations were performed during abdominal procedures. The duration of anaesthesia was 207 ± 96 minutes.

At $f = 20$ cycles/minute an approximately direct proportionality existed between tidal volume and body weight. The regression equation was $V_{T_{\text{pat}}} = 12.3 \cdot \text{kg b.w.} - 2.1$ and the mean value

12.1 ± 1.4 ml/kg b.w. ($P_a\text{CO}_2$ 3.7 ± 0.14 kPa).

At $f = 15$ cycles/minute a rectilinear relationship was recorded between the tidal volume and kg b.w. The regression equation was $V_{T_{\text{pat}}} = 14.6 \cdot \text{kg b.w.} + 16$ and the mean value 15.9 ± 1.5 ml/kg b.w. ($P_a\text{CO}_2$ 3.9 ± 0.11 kPa).

A significant decrease in total compliance was recorded during the initial part of the surgical procedure. The mean value of $C_{T_{\text{TOT}}}$ / kg b.w. was 9.7 ± 0.54 ml/kPa/kg at $f = 20$ cycles/minute. The endotracheal peak pressure maintained a fairly constant pressure level independent of the initial pressure within the ventilator, the tidal volume and the body weight.

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ACKNOWLEDGEMENTS

I would like to express my gratitude to my tutor, Assistant Professor Ludvig Okmian, who also initiated this study.

I would also like to thank Assistant Professors Måns Arborelius Jr, Jan Kugelberg and Dick Thomson for smooth cooperation.

My warm thanks are also expressed to Mrs Birgit Andersson, Mrs Boel Donelius, Miss Gun Hansson, Mr Sigvard Kervall, Mrs Britt Nihlén, Miss Siv Nilsson and Mrs Maily Okmian for their skilful technical assistance and to Mrs Gudrun Jungkvist and Mr Lars Skareke B.A., for the statistical calculations.

I am also indebted to Mr Jan Strömblad, for excellent illustrations, to the personnel on the operative ward and physiological laboratory and to my family for their patience, help and understanding.

The English was revised by David Allen M.D.

These investigations were supported by grants from the Swedish Medical Research Council, Projects No. B75-14X-4519-01, B76-17X-4519-02 and B76-17X-2554-08.

EXPERIMENTAL STUDIES ON ARTIFICIAL
VENTILATION USING THE TVM-VENTILATOR
I. Mechanics of ventilation

STEN LINDAHL and LUDVIG OKMIAN

From the Department of Paediatric Surgery, University Hospital,
S-221 85 Lund, Sweden

Short running title: TVM-ventilator - Mechanics of ventilation

ABSTRACT

The mechanics of ventilation in the piglet and the accuracy of dosage of respiratory volumes were studied under anaesthesia and controlled ventilation using the TVM-ventilator (Tidal Volume Monitoring). A linear relationship was shown to exist between tidal volume and end-inspiratory tracheal pressure and between tidal volume and insufflation time. The TVM-ventilator's tracheal pressure profile reduced the insufflation time to about 50 % of previously registered values. The error between set and registered tidal volume was found to be 6.0 ± 2.7 %.

Total compliance in the piglet (C_{TOT}) correlated to body weight followed the equation $C_{TOT} \text{ (ml/kPa)} = 8.55 \cdot \text{kg b.w.} + 46.9$. Coefficient of correlation was 0.85. $C_{TOT}/\text{kg b.w.}$ was found to be $15.4 \pm 5.0 \text{ ml/kPa/kg}$. The average value C_{TOT}/kg was greater than that in infants.

Nowadays there are technical aids available for proper judgement of gas transport during artificial ventilation in the neonate. Guiding principles for optimal mechanics of ventilation are, however, still under debate. Large single breaths as a result of low respiratory frequency are believed to reduce complications such as atelectasis by improving gas distribution (OKMIAN 1963, HEDLEY-WHYTE et al 1964, OKMIAN et al 1966, OWEN-THOMAS 1966). A similar effect has also been suggested concerning the plateau phase of the insufflation pressure (NORLANDER et al 1968). On the other hand a high tracheal pressure following large single breaths may have a deleterious effect on the pulmonary blood flow (WERKÖ 1947, COURNAND et al 1948, HEDLEY-WHYTE et al 1964, MORGAN et al 1966). Small tidal volumes and high respiratory frequency lessen the risk of damage to the lungs and disturbances of perfusion by high transpulmonary pressure (JONZON et al 1971, NORDSTRÖM 1972), but imply a large physiological dead space ventilation and probably uneven gas distribution.

Adequate gas transport with controlled ventilation can be accomplished with quite different respiratory frequencies provided that the ventilator allows reliable measurement of tidal volume. Increased knowledge about the interaction between respiratory volume, endo-tracheal pressure, insufflation time, gas distribution and lung perfusion may lead to a proper choice of respiratory frequencies in different age groups.

This study presents some characteristics of the mechanics of ventilation with controlled ventilation of piglets using the TVM-ventilator (OKMIAN 1973, OKMIAN et al 1974). The purpose was to shape a basis for evaluation of ventilatory data in animals of body size corresponding to the neonate and infants. In addition, features of the new ventilator are presented. Succeeding communications will deal with specific effects of the dynamic course of insufflation and of ventilatory pattern on gas distribution and pulmonary circulation.

MATERIAL

In total 20 examinations were carried out on 8 Swedish native breed piglets with body weights of 2.7 - 24.5 kg (Table 1). Three of the animals (Nos. I, II, and IV) were each examined twice with an interval of a few days. Two of the animals (Nos. VII and VIII) were followed longitudinally. They weighed 3.4 and 3.7 kg, respectively, at the first examination. After 6 and 5 measurements at intervals of about 8 days their weights had increased to 23 and 24.5 kg, respectively.

METHODS

Total compliance was used as a criterion of the piglets' mechanics of ventilation. By definition it denotes the pulmonary change in volume per unit change in tracheal pressure, measured at the end of each breath under static conditions. To determine total compliance tidal volume and the endo-tracheal pressure at the end of inspiration were registered simultaneously.

Special interest was given to the time taken to bring about a volumetrically completed insufflation (duration of insufflation) which theoretically determines the upper limit for ventilatory frequency. The fall in pressure during insufflation in the ventilator's pressure chamber reflects the dynamic course of events of lung expansion during insufflation (OKMIAN et al 1974).

The ventilator's volume dosage was checked by measurements of the expired gas in a standard gas meter.

Anaesthesia

A combination of Dridol (Droperidolum INN) 1 - 2 mg/kg b.w. and Ketalar (Ketaminum NFN) 30 - 50 mg/kg b.w. intramuscularly was used as anaesthetic agent. The animals were intubated with a

TABLE 1. Actual body weights (kg) for the examined piglets in the series.

Piglet		Examination			No.	
No.	1	2	3	4	5	6
I	9.8	10.5				
II	6.8	7.0				
III	19.5					
IV	2.9	2.7				
V	16.0					
VI	16.0					
VII	3.4	5.0	8.8	10.0	15.0	23.0
VIII	3.7	4.8	9.8	14.5	24.5	

cuffed orotracheal tube and ventilated with air. Alloferin (Alcuronum NFN) in a dose of 1 - 2 mg intravenously was used for muscle relaxation when needed. On completion of the examination Neostigmin (Synstigminum NFN) 1 - 2 mg was injected intravenously.

Symbols

b.w.	Body weight, (kg),
C_{TOT}	Total compliance, (ml/kPa),
f	Ventilatory frequency, (cycles/minute),
P_{ei}	End-inspiratory tracheal pressure, (kPa),
V_T gas meter	The volume of a single breath in ml, calculated from the expired minute volume measured by gas meter,
V_T vent	Tidal volume, read on the ventilator's dial, (ml).

Apparatus and technique

The volume of a single breath

Inspired and expired volumes were recorded and compared. The ventilator displays the volume of gas leaving the compression chamber ($V_{T \text{ vent}}$, ml) on a dial.

The mean volume of a single breath expired gas was estimated by a gas meter for periods of 5 minutes (Standard gas meter, AB Nordgas, Stockholm, Fig. 1).

Pressure measurement

Electrodynamic pressure gauges (Siemens-Elema, EMT 34, EMT 31), amplifiers and ink-jet-recorder (Siemens-Elema 81) were used. The pressure gauges were connected via a polyvinyl catheter ($ID_0 = 2 \text{ mm}$, 2 mm wall thickness, Fig. 1).

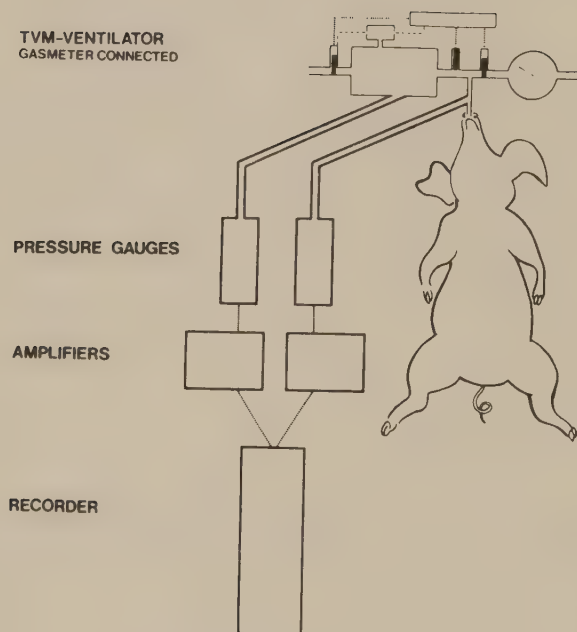


Fig. 1. Schematic representation of experimental set up.

Calibration

The pressure gauges were calibrated simultaneously by water manometer. A pressure gradient of 2.94 kPa (30 cm H₂O) was produced by a pressure flange in a pipe. The water manometer's height was set by alteration of gas flow. Calibrations were carried out after every new ventilatory setting.

Statistics

Current methods for mean values, standard deviation and regression analysis were used.

Procedure

The experimental set up is shown schematically in Fig. 1. Following anaesthesia and orotracheal intubation the experimental animal was connected to the TVM-ventilator. Air was used as respiratory gas.

The animals were placed on their left sides on a warmed operating table with continuous recording of rectal temperature. The temperature was kept between 36° and 38°C by means of the warming apparatus. The examination took on average 1.5 to 2.5 hours to carry out.

The ventilator was set at 20 respiratory cycles per minute and each examination was begun with the ventilator giving large tidal volumes. The tidal volume was then reduced gradually to minimum ventilation and thereafter slowly increased again to the original values. End-inspiratory pressure and volume were read off from the ventilator's instrument dials at each setting of tidal volume. The expired 5 minute volume measured on the gas meter connected to the ventilator and the pressures in both the ventilator's pressure chamber and the animal's tracheal connection were also recorded. The mean tidal volume was derived from the expired 5 minute volume. Those animals which were required to recover from the examination were allowed to regain spontaneous breathing before extubation.

RESULTS

Tracheal pressure and end-inspiratory conditions

Figure 2 shows the characteristic tracheal pressure profiles. The pressure curve drops hyperbolically from the initial peak to a horizontal plateau showing the end-inspiratory value in 6 recordings. The plateau represents equilibration between the pressure in the ventilator's pressure chamber and the lungs. This signifies non-existent gas flow between the compartments.

Insufflation time

Plateau pressure was recorded after 0.47 ± 0.12 s for breaths of differing volumes in 170 insufflations from 20 examinations (range 0.23 - 0.7 s). The insufflation time could be correlated to the tidal volume. A linear relationship was found to exist between the magnitude of the tidal volume and the insufflation time (Fig. 2).

Tidal volume

On 170 occasions the tidal volume set on the ventilator was compared to the calculated value obtained from the expired volume measured on the gas meter. The average value $V_{T \text{ vent}}/V_{T \text{ gas meter}}$ was 1.06 ± 0.027 (percentile difference between set and measured volume was 6.0 ± 2.7 %).

Total compliance and tidal volume

To all intents and purposes a linear relationship was shown to exist between tidal volumes of different values and the corresponding tracheal pressures (Fig. 3). The values for total compliance were lower when increasing tidal volumes than when tidal volumes were decreased.

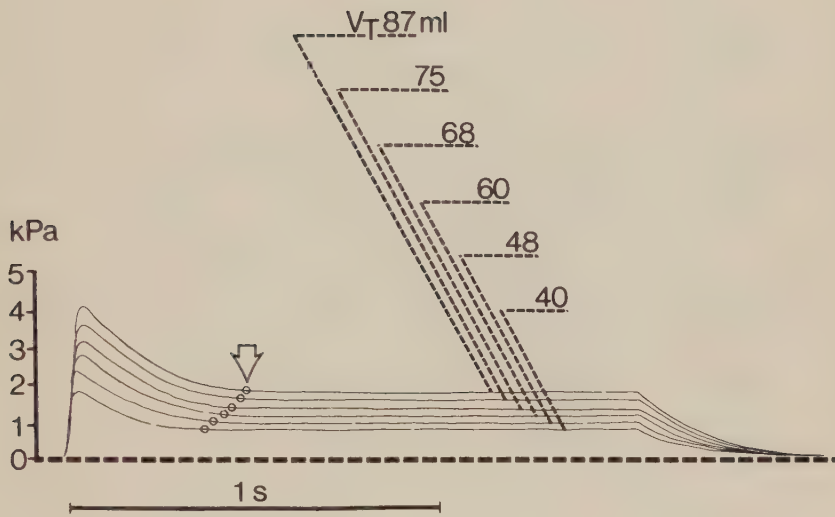


Fig. 2. Six pressure recordings during insufflation of different tidal volumes (40 - 87 ml) in the same experimental animal. Open circles show completed insufflation. The arrow marks the linear relationship volume/insufflation.

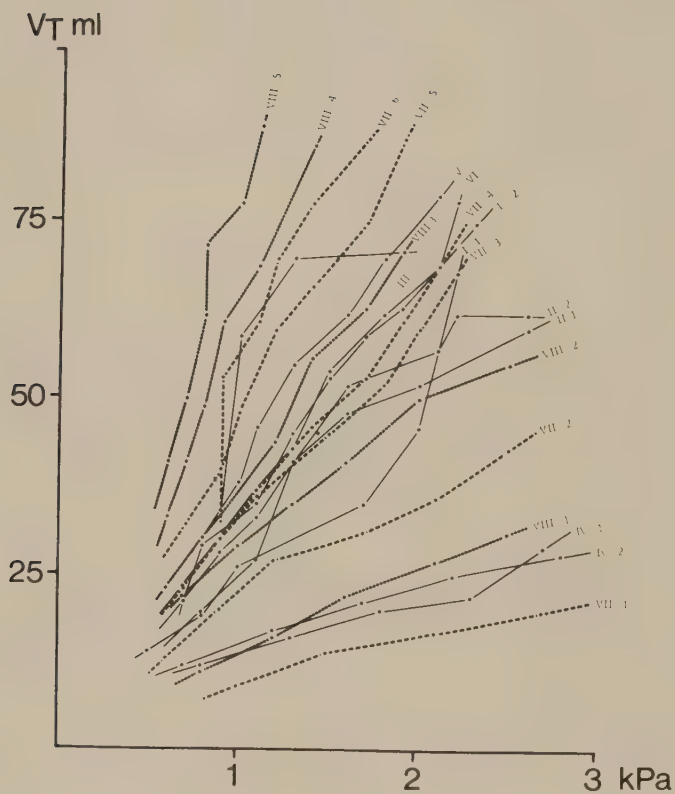


Fig. 3. Tidal volume and corresponding end-inspiratory pressure for progressively enlarged breaths. The roman figures refer to the experimental animals. Dotted lines represent longitudinal examinations of piglets Nos. VII and VIII. Arabic figures denote the number of examination. For further data, see Table 1.

Total compliance and body weight

The average values for total compliance from 92 comparable examinations correlated to the animal's body weight are shown in Fig. 4. Regression equation $C_{TOT} = 8.55 \cdot \text{kg b.w.} + 46.9 \text{ ml/kPa}$, ($C_{TOT} = 0.85 \cdot \text{kg b.w.} + 4.9 \text{ ml/cm H}_2\text{O}$). Coefficient of correlation 0.85 (Fig. 4). The average value for C_{TOT} per kg b.w. = $15.4 \pm 5.0 \text{ ml/kPa/kg}$ ($C_{TOT}/\text{kg b.w.} = 1.51 \pm 0.49 \text{ ml/cm H}_2\text{O/kg}$).

DISCUSSION

The mechanical properties of the lungs and airways with controlled ventilation have previously been comprehensively studied. OPIE et al (1959) recorded insufflation time of 0.9 - 1.25 s in paralyzed adult human subjects using the Radcliffe ventilator. OKMIAN et al (1966) found values of about 1.2 s using an Engström ventilator in infants with frequencies of 10 to 20 cycles per minute. Compared to these earlier clinical values for insufflation time, a reduction of 50 % has been recorded in this experimental study.

The pressure curves obtained with different tidal volumes in the same animal were almost congruent in form. It follows that the insufflation time increased proportionally with tidal volume. The mean value for insufflation time of 0.47 s and the standard deviation from the mean of 0.12 s gave an upper limit for frequency of 50 cycles per minute with small tidal volumes, inspiration and expiration being of equal duration.

The fact that the reduction in insufflation time is due to the mode of action of the TVM-ventilator and not influenced by the experimental conditions has been shown by simultaneous studies with different ventilators (OKMIAN et al 1974). Applied clinically, this reduction in insufflation time allows correspondingly increased inspiratory frequencies which widens the scope for treatment of infants with pronounced lung pathology.

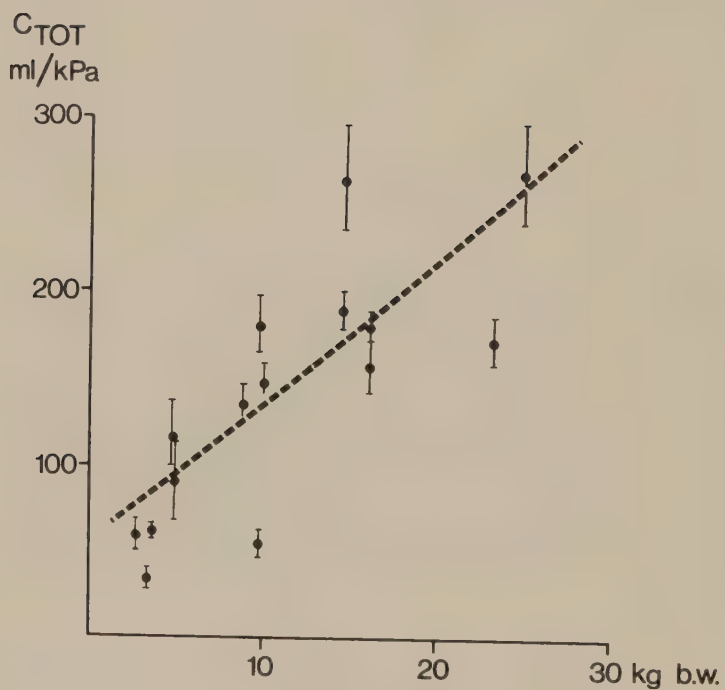


Fig. 4. Total compliance in relation to body weight (kg). The regression line is shown broken. Regression equation C_{TOT} (ml/kPa) = $8.55 \cdot \text{kg b.w.} + 46.9$.

In practice, a steady state for lung ventilation on unchanged ventilatory settings can only be achieved for limited periods. During operation tidal volume can be reduced by over 50 % by surgical manipulation such as pressure from retractors etc (OKMIAN et al 1966). Similar effects can be seen in the infant treated on a ventilator for IRDS on crying or breathing against the ventilator. The infant's diurnal rhythm, state of awareness, activity and meal times also influenced the volume of ventilation through changes in muscle tone, position and pressure of abdominal organs against the diaphragm. Under such circumstances it is of great value to be able to record the volume of ventilation breath by breath on the ventilator and to be able to regulate the tidal volume. MATTILA (1974) expressed the same conclusion in his review and analysis of apparatus designed for ventilation of infants. The TVM-ventilator includes a new system for determination of tidal volumes based on the 2-pressure method (OKMIAN 1963). Special attention has also been paid to the study of the accuracy of volume dosage. The error between the tidal volume set and that measured amounted to a systematic difference of 6.0 ± 2.7 %; in other words, the set tidal volume of 20 ml lay within the range 21.3 ± 0.5 ml. The error is thus minimal especially as no correction was made for the difference in temperature between inspired and expired gas and as the determinations of expired volume were calculated from 5 minute-volumes.

Using the TVM-ventilator the volume of ventilation is regulated by setting the tidal volume and the frequency instead of minute volume and frequency as in former apparatus. This setting principle allows regulation of the mechanics of ventilation without interference in gas transport. This is, from a practical point of view, a considerable advantage.

Both the relationship of tidal volume to the tracheal pressure and total compliance to body weight have previously been estimated in infants under anaesthesia before and during the operation. In this experimental study we found a linear relationship between tidal volume and end-inspiratory tracheal pressure (total compliance). The same conditions have been shown to exist in infants. The regression equation for total compliance to kg b.w. in infants was shown to be $C_{TOT} \text{ (ml/cm H}_2\text{O)} = 0.9 \cdot \text{kg b.w.} + 0.04$ (OK-

MIAN et al 1966), and for piglets C_{TOT} (ml/cm H₂O) = 0.85 · kg b.w. + 4.9. The average values for C_{TOT} per kg b.w. were calculated to be, respectively, 0.88 ± 0.18 ml/cm H₂O/kg and 1.51 ± 0.49 ml/cm H₂O/kg. The difference between the mean values may be explained by the different species and methods used. In addition, among the infants there were also several individuals with pulmonary diseases.

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EXPERIMENTAL STUDIES ON ARTIFICIAL
VENTILATION USING THE TVM-VENTILATOR
II. Dynamics of insufflation

STEN LINDAHL and LUDVIG OKMIAN

From the Department of Paediatric Surgery, University Hospital,
S-221 85 Lund, Sweden

Short running title: TVM-ventilator - Dynamics of insufflation

ABSTRACT

The influence of a ventilator's volume pressure characteristics (C_{vent} , internal compliance) on the dynamic course of insufflation was studied during artificial ventilation with a TVM-ventilator (Tidal Volume Monitoring) on 23 piglets with body weights between 2.4 and 24.5 kg.

For evaluation of the dynamics of insufflation the instantaneously delivered breathing gas and the corresponding tracheal pressure were recorded. Reverse plethysmography was used for the volume measurements.

During insufflation a linear relationship was found between the amount of delivered breathing gas and the pressure in the airways.

The linear relationship was not influenced either by the individual's body size, total compliance or tidal volume.

The ventilator's volume/pressure characteristics did, however, significantly influence the tracheal peak pressure and the size of the direction coefficient for the linear dynamic volume/pressure relation during insufflation as well as the duration of the insufflation. A low volume/pressure ratio resulted in a high peak pressure and a short insufflation time. The optimal C_{vent} could not be estimated but the investigation opened ways for an objective evaluation of a ventilator's efficiency, the relationship between endotracheal pressure and gas transport, as well as the dynamic course of insufflation.

The instantaneous tracheal pressure during artificial endotracheal ventilation, is a result of the mutual interaction of the amount of insufflated breathing gas per unit time, and airway and elastic pulmonary resistance. In connection with this the instantaneous volume/pressure relationship reflects a complex dynamic course. The dynamics of insufflation give certain possibilities for evaluation of the ventilator and the breathing organs. However, only a few investigations have hitherto been reported in this area (NORLANDER 1964, PESLIN 1969).

This work deals with the dynamic course of insufflation during ventilation of piglets with the TVM-ventilator (OKMIAN 1973) as well as the effect of body size, tidal volume and the ventilator's volume/pressure characteristics on the dynamics of insufflation.

MATERIAL

23 piglets of the Swedish native breed were investigated on 35 occasions.

In 19 examinations the influence of body size on the dynamics of insufflation was studied on 6 piglets with body weights between 2.4 and 24.5 kg. Two of the animals were used in 2 investigations while 2 other animals were followed longitudinally with 5 and 6 investigations, respectively, with one week intervals. Four animals were used in only one experiment.

The effect of tidal volume on the dynamic course of insufflation was studied on 6 piglets during 6 investigations. The body weights were between 7 and 12 kg (mean 8.6 kg).

The effect of the ventilator's volume/pressure ratio on the dynamics of insufflation was studied in 11 piglets on 11 occasions. The body weights were between 6.5 and 12.0 kg (mean 8.1 kg).

SYMBOLS

b.w.	Body weight, (kg),
C_{TOT}	Total compliance, (ml/kPa),
C_{vent}	Ventilator volume/pressure quotient, (ml/kPa),
f	Ventilatory frequency, (cycles/minute),
ΔP	Instantaneous pressure change, (kPa),
P_B	Atmospheric pressure, (kPa),
P_{ei}	End-inspiratory tracheal pressure, (kPa),
P_{peak}	Tracheal peak pressure, (kPa),
Δt	Insufflation/unit time, (0.1 s),
t_{insuff}	Duration of insufflation, (s),
ΔV	Instantaneous gas amount change, (ml),
$V_{T_{exp}}$	Tidal volume, expired gas corrected to BTPS, (ml).

METHODS

The piglets were ventilated artificially with a TVM-ventilator (Tidal Volume Monitoring). The effects on the course of insufflation of body size, tidal volume and the ventilator's volume/pressure quotient were studied by registration of the corresponding changes in the volume of breathing gas and endotracheal pressure.

The relationship between gas volume and endotracheal pressure during insufflation is presented in a right-angle-coordinate system with the pressure coordinates along the abscissa. The regression equation for the relationship and the regression-line's angle with the abscissa are calculated. The evaluation of the results was made statistically with paired significance testing according to Student's t-test.

In principle, reverse plethysmography with the TVM-ventilator as a plethysmograph, is used for the registration of the instantaneous amount of breathing gas which has left the ventilator (Fig. 1). Conditions for making the measurements were given by the rigid-walled construction of the TVM-ventilator's pressure chamber and its

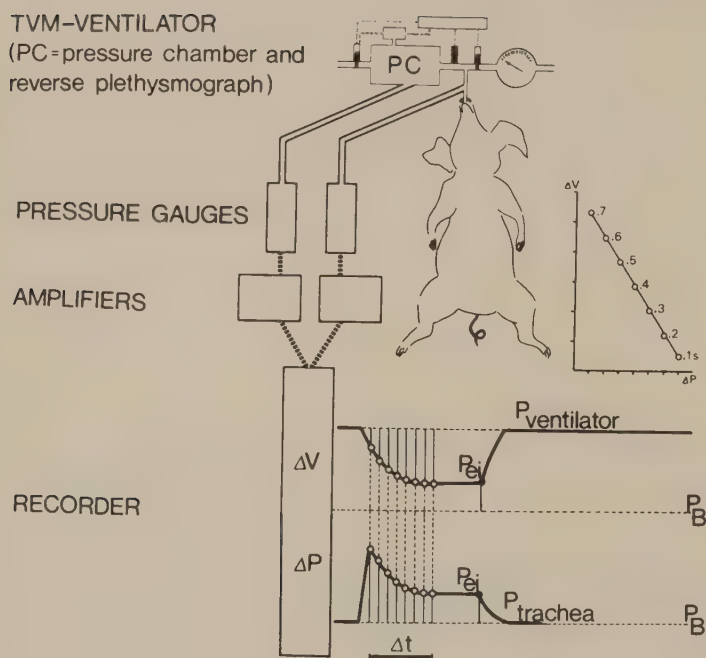


Fig. 1. Schematic presentation of the method. The curve for the pressure in the pressure chamber ($P_{ventilator}$) also represents the amount of gas that passes over from the ventilator to the airways (ΔV). The lines drawn to the circles represent the gas amounts. The lines drawn to the open circles on the curve $P_{trachea}$ represent the corresponding tracheal pressure (ΔP). The diagram $\Delta V / \Delta P$ represents the instantaneous relationship between the gas amount and the gas pressure during insufflation.

working principle. Every pressure change in the ventilator's pressure chamber corresponds to a certain amount of gas (LINDAHL & OKMIAN 1977). Thus, on inspiration the pressure in the ventilator's pressure chamber decreased in proportion to the amount of gas that left the ventilator. The determination of the amount of gas as gas pressure could be measured electromanometrically (Siemens-Elema EMT 34). The recordings were registered simultaneously with a direct recorder (Siemens-Elema EM 81).

The calibration of the expressed pressure was made regularly before and after every registration against a water manometer with a 30 cm high water column. The linearity of the measuring device in the actual pressure range used and the synchronicity of the registrations were controlled.

The volume/pressure ratio (C_{vent}) of the TVM-ventilator can be set at 20 ml/kPa, 40 ml/kPa, 60 ml/kPa, and 80 ml/kPa. With these adjustments the size of the ventilator's pressure chamber is changed.

PROCEDURES

The animals were fasted for at least four hours before the start of the investigations. Cuffed plastic tubes were used for oral intubation. During all investigations room air without any added gases was used.

A combination of Dridol (Droperidolum INN) 1 - 2 mg/kg b.w. and Ketalar (Ketaminum NFN) 30 - 50 mg/kg b.w. intramuscularly were used as anaesthetic agent. Alloferin (Alcuronium NFN) in doses of 1 - 2 mg was given intravenously for muscle relaxation. After the completion of the investigation, Neostigmin (Synstigminum NFN) 1 - 2 mg was injected intravenously into the animals so that they could be examined later after growth. The other animals were sacrificed during anaesthesia.

After anaesthesia and oral intubation the piglets were connected to the TVM-ventilator and the measuring devices.

Body size

All animals in the examination series were ventilated with a frequency of 20 cycles/minute and a ventilator volume/pressure quotient of 40 ml/kPa. All the investigations began with large tidal volumes which were successively reduced. Every animal was ventilated with 4 - 5 breaths of varying size. A normal tidal volume (15 ml/kg) was chosen for dealing with the dynamic course of the breath.

Tidal volume

On 6 piglets in the same weight class the tidal volume was adjusted to normoventilation or mild hyperventilation with the aid of infra-red CO₂-analyses of alveolar gas via an end-tidal sampler (Godhart, Holland). With frequencies of 10.3 cycles/minute and 30 cycles/minute and 20 % and 50 % inspiration fractions respectively, tidal volumes of varying size could be exhibited with the same duration of insufflation. The volume/pressure quotient of the ventilator was 40 ml/kPa. A ventilatory steady state was reached by ventilating the animals at least 10 minutes with unchanged ventilator settings before each registration.

Ventilator volume/pressure quotient

The normoventilation was set according to the above with infra-red CO₂-analyses of the expired gas at a ventilatory frequency of 20 cycles/minute and an inspiration fraction of 33 % of the breathing cycle. The trial began with a volume/pressure ratio of 20 ml/kPa. Registration began after 10 minutes of ventilation with unchanged settings on the ventilator. The procedure was repeated with the quotient 80 ml/kPa. The frequency, tidal volume, and inspiratory fraction were held unchanged during all registrations.

RESULTS

Body size, total compliance

For all registered tidal volumes it was found that after the peak pressure was reached during insufflation, there was a linear relationship between the corresponding volumes and pressures. The mean value of the direction coefficient for the 19 individual volume/pressure relationships corresponded to the cotangent of the direction angle $98^{\circ} \pm 0.6$ (Fig. 2). The body size of the individual and total compliance (Fig. 3) did not have any effect on the dynamic course of insufflation with respect to linearity and angle direction.

Tidal volume

The tidal volume did not influence the dynamic course of insufflation. A linear volume/pressure relationship was shown for large as well as for small tidal volumes. The mean values of the regression coefficients for both large and small tidal volumes corresponded to the cotangent for the direction angles $98^{\circ} \pm 1.4^{\circ}$ and $98^{\circ} \pm 1.6^{\circ}$ (n.s., Fig. 4).

Ventilator volume/pressure quotient

The linear relationship between the corresponding volumes of breathing gas and the endotracheal pressure was registered with both C_{vent} settings.

The average values for the regression coefficients for $C_{vent} 20$ and $C_{vent} 80$ ml/kPa, respectively, corresponded to the cotangent for the respective direction angles $104^{\circ} \pm 0.84^{\circ}$ as well as $93^{\circ} \pm 0.33^{\circ}$ (Fig. 5). The difference was significant ($p < 0.01$).

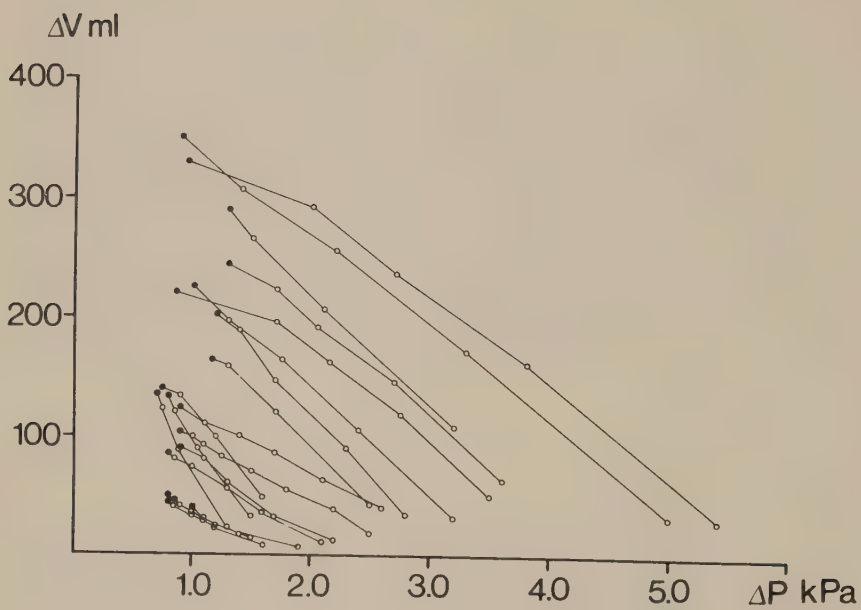


Fig. 2. The instantaneous volume/pressure relationship during insufflation on animals of different body size during normoventilation (open circles). Filled circles represent the end-tidal tracheal pressure.

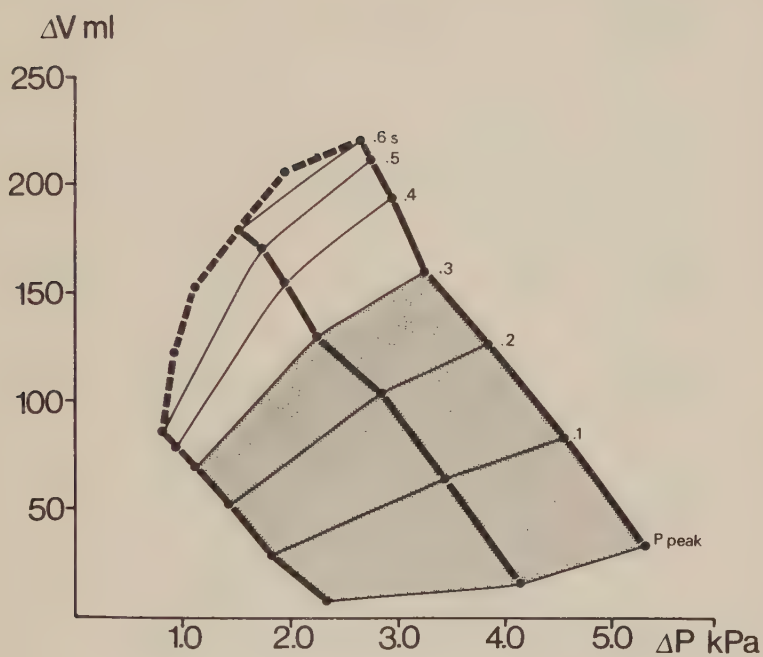


Fig. 3. The dynamic course of three different tidal volumes from one animal (thick continuous lines). Total compliance is represented by the thick dotted line. The volume pressure relationship ($\Delta V / \Delta P$) for every tenth of a second during insufflation is represented by thin lines.

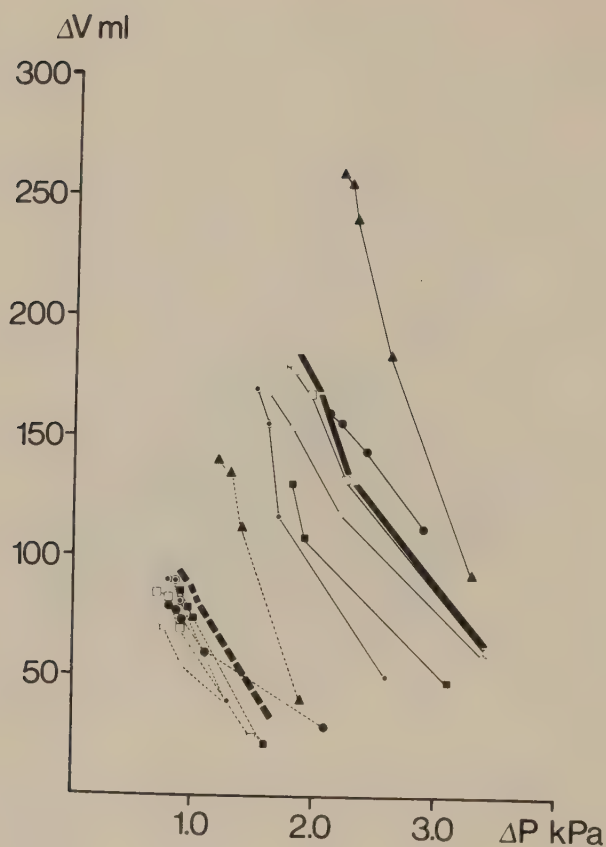


Fig. 4. The instantaneous volume/pressure relationship with different tidal volumes on six animals of approximately the same body size. Every animal has its own symbol (open circles, filled circles, triangles, squares, etc). The small dotted lines connect observations during small tidal volumes. The thin continuous lines connect observations during large tidal volumes. The thick dotted lines and the thick continuous line represent the mean values for the corresponding group.

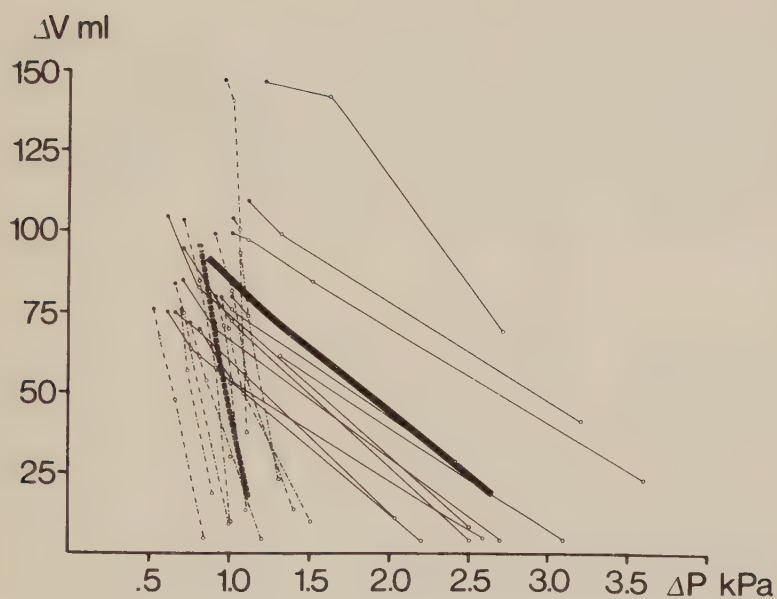


Fig. 5. The instantaneous volume/pressure relationship for the ventilator's volume/pressure ratio 20 ml/kPa (continuous lines) and 80 ml/kPa (dotted lines). The mean values are represented by the corresponding thick lines.

The mean values of the peak pressures with C_{vent} 20 ml/kPa were 2.6 ± 0.12 kPa and with C_{vent} 80 ml/kPa 1.1 ± 0.06 kPa. The difference was significant ($p < 0.001$, Table 1).

During ventilation with volume/pressure ratio 20 ml/kPa the duration of insufflation was recorded as 0.23 ± 0.01 s and with 80 ml/kPa, 0.38 ± 0.01 s. The difference was significant ($p < 0.001$, Table 1).

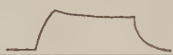
The volume/pressure ratio 20 ml/kPa meant larger resources available to overcome airway resistance. The area between the two ratios (shadowed in Fig. 6) shows this graphically. This additional energy reduced the duration of insufflation.

DISCUSSION

Since the end of the 1950s' methods of delivering artificial ventilation have been subjected to evaluation by physical model experiments, animal experiments and clinical series (BERGMAN 1967, LYAGER 1968, BAKER 1971, HEDENSTIERNA & JOHANSSON 1972, JANSSON & JONSON 1972, NORDSTRÖM 1972). Certain presumed advantages with accelerated gas flow were emphasized at an early stage (ENGSTRÖM 1963, HERZOG & NORLANDER 1968), while in later studies there was also shown to be an advantage in constant and decelerating gas flow (JOHANSSON & LÖFSTRÖM 1975). As a basis for earlier judgements chiefly minute ventilation, end-tidal pressure and average value of the gas analyses have been used. The instantaneous volume/pressure relationship during insufflation has earlier been of little or no concern, although it would be quite a reasonable parameter to use for defining the ventilatory response of different endotracheal pressure profiles.

Pneumotachygraphy has chiefly been used previously for the simultaneous measurement of the amount of breathing gas that left the ventilator and the corresponding endotracheal pressure (GRENVIK & HEDSTRAND 1966). In this investigation reverse plethysmo-

TABLE 1. The values measured (mean values and standard error of mean) during ventilation with two volume/pressure ratios on the ventilator ($\alpha = \cot \Delta V / \Delta P$, ★★★ = $p < 0.001$, ★★ = $p < 0.01$, ★ = $p < 0.05$).

Tracheal profile			Difference, %, and significance	
C_{vent}	20	80	-	
f	20	20	-	
n	11	11	-	
P_{peak}	2.6 ± 0.12	1.1 ± 0.06	-58 %	★★★
P_{ei}	0.82 ± 0.06	0.79 ± 0.05	-4 %	n.s.
t_{insuff}	0.23 ± 0.01	0.38 ± 0.01	+65 %	★★★
$V_{T_{exp}}$	93 ± 6.9	94 ± 5.0	+1 %	n.s.
C_{TOT}	115 ± 8.0	120 ± 7.4	+4.5 %	n.s.
α	$104^{\circ} \pm 0.84^{\circ}$	$93^{\circ} \pm 0.33^{\circ}$	-11 %	★★

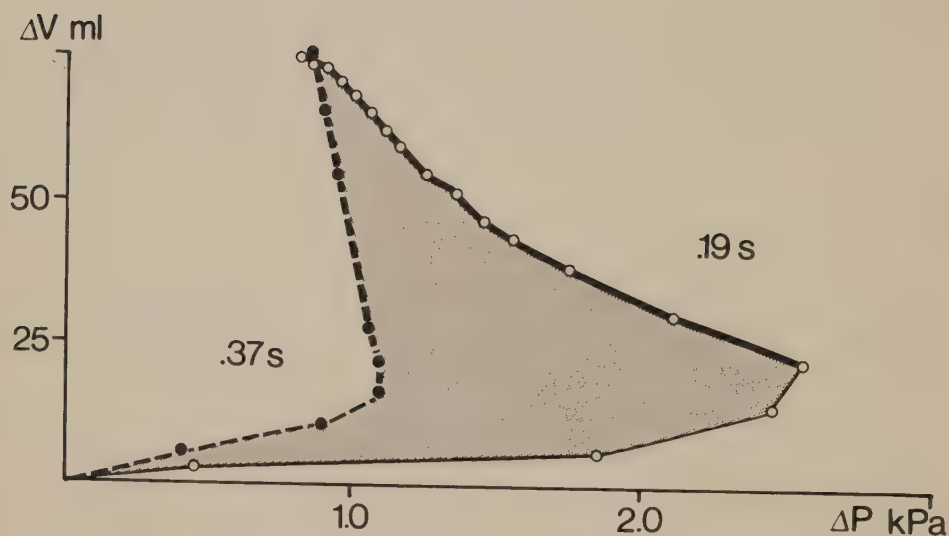


Fig. 6. The dynamic course of two equally large breaths carried out with the ventilator's volume/pressure quotient 20 ml/kPa (open circles) and 80 ml/kPa (filled circles). The area of the shadowed region between the curves represents the increase of the work of breathing required to overcome airway resistance. The effect of the increased energy is reflected in the shorter time for insufflation (0.19 s).

graphy is used for the first time as far as we know. Reverse plethysmography is as a measuring method fairly free from disadvantages as the pressure chamber of the TVM-ventilator consists of rigid-walled material and its volume remains unchanged during the whole breathing cycle.

In determining the amount of gas with reverse plethysmography, the accuracy of the measurements is dependent upon the pressure registrations. The method is thus both simple and accurate. With pneumotachygraphy, however, it is necessary to connect the recording instrument to the ventilation system. In addition, the results with pneumotachygraphy are influenced by many physical factors such as the composition of the gases, viscosity, humidity, temperature and flow rate etc (GRENVIK & HEDSTRAND 1966).

The choice of experimental animal was dictated by the desire to have the same lung size as in infants during ventilation. In earlier published investigations (LINDAHL & OKMIAN 1977) mechanics of ventilation of value for the evaluation of methods and results have been shown. These data also show the suitability of the experimental species for these kinds of investigations.

The result of the examinations showed that during inspiration there existed a linear relationship between the amount of breathing gas that left the ventilator and the pressure in the airways. The linearity was not influenced by the individual tidal volume or by the individual body size. When the ventilator's volume/pressure characteristics were changed, there was still a linear relationship. On the other hand, the line direction coefficient was markedly affected, i.e. the angle that it formed with the horizontal axis in a coordinate system.

The explanation of the phenomenon is that changes in the size of the TVM-ventilator's volume/pressure ratio are brought about by increasing or decreasing the size of the pressure chamber. The ratio 80 ml/kPa means approximately a pressure chamber four times larger than for the ratio 20 ml/kPa. If the pressure chamber is used for the production of the same tidal volumes then the initial pressure during insufflation becomes four times larger for

the smaller pressure chamber than for the larger. The endotracheal pressure thus reflects the available energy for insufflation. The higher initial tracheal pressure at volume/pressure ratio 20 ml/kPa represents significantly more energy to overcome airway resistance.

It has earlier been reported that for human beings (OKMIAN et al 1966) as well as for animals a linear relationship exists between the tidal volume during artificial ventilation and the prevailing end-tidal pressure, i.e. total compliance (LINDAHL & OKMIAN 1977). OKMIAN et al also showed that the volume/pressure relationship with ventilation of infants with accelerating gas flow was not linear. The contradictory results in our investigation are explained by the difference in the working principle of the ventilator. The TVM-ventilator works with a decelerating gas flow. When the inspiratory valve opens the airway is connected with a pressure chamber in which the tidal volume is compressed. The pressure increases instantaneously in the airway and in 1/10 of a s the pressure has reached its peak value. This is followed by an equilibration of pressure depending on airway resistance and lung compliance, i.e. the volume increase follows physical laws. The TVM-ventilator's working principle produces in other words a standardized tracheal curve profile for the volume/pressure relationship which can be used for a detailed study of the dynamic course of insufflation.

The most obvious effect of the power increase with the volume/pressure ratio 20 ml/kPa was that the time required for transferring the gas mass past the airway resistance to the alveoli was significantly reduced. In Figure 6 the size of the increase in the work of breathing is illustrated graphically in the area that is drawn between the two curves for volume and pressure during insufflation using different volume/pressure ratios.

Assessment of the ventilator's respiratory capacity has earlier been the subject for detailed investigations. NORLANDER (1964) tried to quantify the work of breathing with computer technique. MAPLESON (1967) used electronic analogue technique for the same purpose. In addition many physical model experiments have been published (among others LYAGER 1968, PESLIN 1969, JANS-SON & JONSON 1972). Comparisons between the efficiency of

different ventilators have also been made on the same patient with blood gas values as a basis (NORDSTRÖM 1972).

Our results showed that the use of greater power from the ventilator or greater ventilatory effect resulted in a significant shortening of the duration of insufflation. As a consequence of this finding it should be possible to use the duration of insufflation as a parameter for the evaluation of the ventilator, tracheal pressure and profiles etc. Duration of insufflation may be carefully measured for example by recording the tracheal pressure or the endotracheal gas flow with a recorder with fast paper speed or with an oscilloscope.

The lack of available data for the choice of a suitable C_{vent} during ventilation of individuals with small body size was an incentive for this investigation. The advantages of a high C_{vent} showed themselves during leakage and with spontaneous breathing with a decreased pressure gradient and increased ventilatory elasticity. The larger pressure chamber naturally gives a larger reserve of compressed gas and smaller pressure differences with asynchronous spontaneous breathing. The low C_{vent} gives mainly a shorter duration of insufflation. The optimal value for the volume/pressure ratio could not be estimated from the results in this investigation. However, several factors of importance for the evaluation of suitable values for the volume/pressure ratio could be singled out. Figure 6 gives a clear illustration of this. A tidal volume of 75 ml is delivered on 0.19 and 0.37 s, respectively, with volume/pressure ratios 20 ml/kPa and 80 ml/kPa. If 1/3 of the whole breathing cycle is assigned for inspiration then the maximum possible frequencies were approximately 105 and 54, i.e. the pulmonary ventilation should increase more than 5 and 2 1/2 times the normoventilation by increasing the ventilatory frequency. The pressure in the ventilator's pressure chamber was, at the C_{vent} of 20 ml/kPa, $3.75 + 0.9 = 4.65$ kPa and at 80 ml/kPa, $0.94 + 0.9 = 1.84$ kPa, but the peak pressure measured in the trachea remained at 2.6 and 1.2 kPa, respectively. A significant reduction in pressure thus occurs instantaneously when the inspiratory valve is opened. The reduction probably increases with increasing body size and dead space but the peak pressure

in these conditions probably undergoes significantly smaller changes. The actual relationship is of significant interest as regards the dimensions of the ventilator's pressure chamber and should be clinically investigated.

The results of our investigation present in several respects new ways of objectively evaluating the ventilator's efficiency, the relationship between endotracheal pressure and gas transport, as well as the dynamic course of insufflation. There is no doubt that the smallest C_{vent} showed the largest ventilatory effect. On the other hand, the possible side-effects of the higher initial peak pressure on gas distribution and lung perfusion still constitute an unknown area which should be investigated before a complete evaluation of the C_{vent} becomes possible.

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EXPERIMENTAL STUDIES ON ARTIFICIAL
VENTILATION USING THE TVM-VENTILATOR
III. Ventilator volume pressure quotient,
pulmonary ventilation, gas distribution,
and lung perfusion

STEN LINDAHL, MÅNS ARBORELIUS Jr and LUDVIG OKMIAN

From the Department of Paediatric Surgery, University Hospital,
S-221 85 Lund, and the Department of Clinical Physiology, Malmö
General Hospital, S-214 01 Malmö, Sweden

Short running title: TVM-ventilator - Influence of ventilator vo-
lume/pressure quotient on pulmonary ventilation, gas distribu-
tion, and lung perfusion

ABSTRACT

Tidal volumes of the same magnitude were delivered to piglets under anaesthesia with muscle relaxation using the TVM-ventilator (Tidal Volume Monitoring) with high and low volume/pressure quotients (C_{vent} 80 ml/kPa and C_{vent} 20 ml/kPa, respectively) both with un-obstructed airways and after bronchial obstruction. The evaluation of the ventilation was carried out by pulmonary mechanical data, quantitative analysis of expired gas, blood gas analyses and Xe^{133} radiospirometry.

With C_{vent} 20 ml/kPa the tidal volumes were insufflated in a shorter time with a higher initial tracheal peak pressure than with C_{vent} 80 ml/kPa. With un-obstructed airways there were no significant differences in arterial blood gases, V_{Dphys}/V_{Texp} ratio, V_A , RQ, gas distribution and lung perfusion between ventilation with C_{vent} 20 compared to that with C_{vent} 80.

Following bronchial obstruction V_A , RQ, and P_aO_2 were greater with C_{vent} 20 than with C_{vent} 80 ml/kPa, while distribution of lung perfusion was unchanged.

The part of inspired gas going to the obstructed area was reduced by 24.1% with C_{vent} 20 and by 21.9% with C_{vent} 80 ml/kPa. In the un-obstructed lung base the ventilation was reduced by 14.9% with C_{vent} 20 while there was an increase by 8.3% with C_{vent} 80 ml/kPa. The decrease in ventilation of the lung bases with C_{vent} 20 was compensated for by a large increase in ventilation within the apical areas of the lungs, while gas distribution within the un-obstructed areas was more evenly distributed with C_{vent} 80. With regional bronchial airway obstruction the magnitude of ventilation was retained but mainly through hyper-expansion of the un-obstructed lung areas.

The results showed that the insufflation time during artificial ventilation reflected the ventilator's efficiency. When the ventilator's performance was defined, measurement of the duration of insufflation enabled evaluation of conditions within the lungs. Ventilation at a low volume/pressure quotient and a high endo-

tracheal peak pressure showed no essential advantages over a high volume/pressure quotient and a low endotracheal peak pressure. Only in lungs extremely difficult to ventilate and with ventilatory frequencies of over 50 cycles/minute could possible indications for low volume/pressure quotients be seen.

On inspiration during artificial ventilation, gas is compressed within the ventilator, its valves and tubing. The compressed gas does not reach the individual's lungs. The amount of compressed gas varies with the size of the endotracheal pressure, and the relationship between the compressed gas in the ventilator and tubing to actual pressure, i.e. the volume/pressure ratio of the system, is specific for the ventilator and connections. The compressed gas volume within the ventilator and tubing complicates exact measurement of expired gas volume from the patient, especially during the treatment of neonates and small infants (OKMIAN 1963). On the other hand, the compressed gas volume provides a reserve during, for example, leakage in the tracheal connection. In addition, a large space within the ventilator gives more freedom for the patient to breathe spontaneously as the risk for damage due to pressure is reduced.

The construction of the TVM- ventilator offers a choice of volume/pressure ratios (C_{vent}) of 20 ml/kPa, 40 ml/kPa, 60 ml/kPa, and 80 ml/kPa by changing the size of the pressure chamber (OKMIAN 1973, OKMIAN et al 1974, LINDAHL & OKMIAN 1977 a). In addition the compressed gas is retained in the ventilator's pressure chamber from one breathing cycle to the next by the aid of the valves. The evaluation of the amount of expired gas is therefore not influenced by the choice of the volume/pressure ratio. This relationship has provided the opportunity of testing the ventilator's dimensions to find suitable pulmonary ventilation.

In an earlier investigation (LINDAHL & OKMIAN 1977 b) it has been shown that a low volume/pressure ratio provided a shorter insufflation time than a high. In the present investigation, mechanics of ventilation, gas transport, distribution of gas and blood within the lungs were examined during normoventilation with a high and a low C_{vent} , both with un-obstructed airways and after bronchial obstruction.

MATERIAL

The examinations were carried out on five piglets of the Swedish native breed. Their body weights were between 7 and 12 kg (mean 8.3 kg).

SYMBOLS

b.w.	Body weight, (kg),
C_{TOT}	Total compliance, (ml/kPa),
C_{vent}	Ventilator volume/pressure quotient, (ml/kPa),
f	Ventilatory frequency, (cycles/minute),
LA	Left pulmonary apex,
LB	Left pulmonary base,
P_aCO_2	Carbon dioxide tension in arterial blood, (kPa),
$\bar{P}_E CO_2$	Mean partial pressure of carbon dioxide in mixed expired gas, (kPa),
P_{ei}	End-inspiratory tracheal pressure, (kPa),
$P_I CO_2$	Partial pressure of carbon dioxide in inspired air, (kPa),
P_{peak}	Tracheal peak pressure, (kPa),
Q_r	Regional pulmonary perfusion, (percentage of total pulmonary perfusion),
RA	Right pulmonary apex,
RB	Right pulmonary base,
RQ	Respiratory quotient,
t_{exsuff}	Duration of exsufflation, (s),
t_{insuff}	Duration of insufflation, (s),
V_A	Alveolar ventilation, (ml),
$\dot{V}_{CO_2}$	Carbon dioxide production, STPD, (ml/min),
$V_{D_{phys}}$	Physiological dead-space, (ml),
$\dot{V}_{O_2}$	Oxygen consumption, STPD, (ml/min),
V_r	Regional pulmonary ventilation, (percentage of total pulmonary ventilation),

$V_{T_{exp}}$	Tidal volume, expired gas corrected to BTPS, (ml),
$V_{T_{vent}}$	Tidal volume, read on the ventilator's dial, (ml).

METHODS

With the TVM-ventilator's volume/pressure quotient (C_{vent}) set at 20 ml/kPa and 80 ml/kPa, tidal volumes can be delivered with different initial pressure gradients between the ventilator and the airways. The size of the pressure gradients influence the size of the initial peak pressure in the trachea. The effect of peak pressure on the mechanics of ventilation, gas transport, distribution of gas, and blood, was investigated before and after bronchial obstruction. A schematic presentation of the experimental set up is shown in Figure 1.

The animals were ventilated with air without additional gases. The same frequency, 20 cycles/minute and an inspiration fraction of 33 % of the breathing cycle, i.e. 1 s for inspiration, were used during all experiments.

Regional bronchial airway obstruction was obtained by inserting a metal cylinder (I.D. = 1 mm, Fig. 2 a) in the right caudal lobe bronchus. The position was controlled by fluoroscopy and by photographs before and after the recordings (Fig. 2 b) and finally controlled again during autopsy. The resistance in the metal cylinder is shown graphically in Figure 2 c.

Anaesthesia

A combination of Dridol (Droperidolum INN) 1 - 2 mg/kg b.w. and Ketalar (Ketaminum NFN) 30 - 50 mg/kg b.w. was injected intramuscularly. The piglets were intubated with a cuffed orotracheal tube and ventilated with room air. Alloferin (Alcuronium NFN) 1 - 2 mg was used intravenously for muscle relaxation when needed.

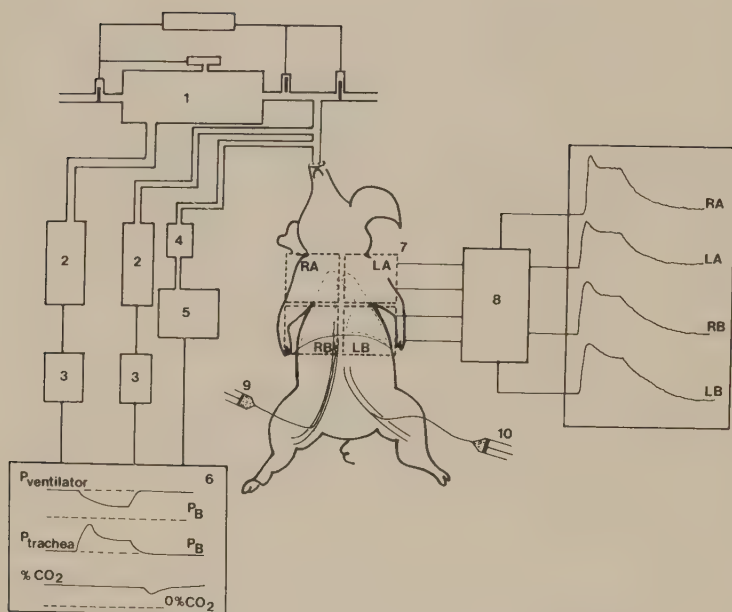


Fig. 1. Schematic presentation of the experimental set up and the method. 1/ The TVM-ventilator with its pressure chamber, PC, valves and electronics. 2/ Pressure gauges. 3/ Amplifiers. 4/ End-tidal sampler. 5/ Infra-red carbon dioxide analyser. 6/ Recorder. 7/ Detectors for radiospirometry. 8/ Computer and printer-plotter. 9/ Central venous catheter. 10/ Arterial catheter.

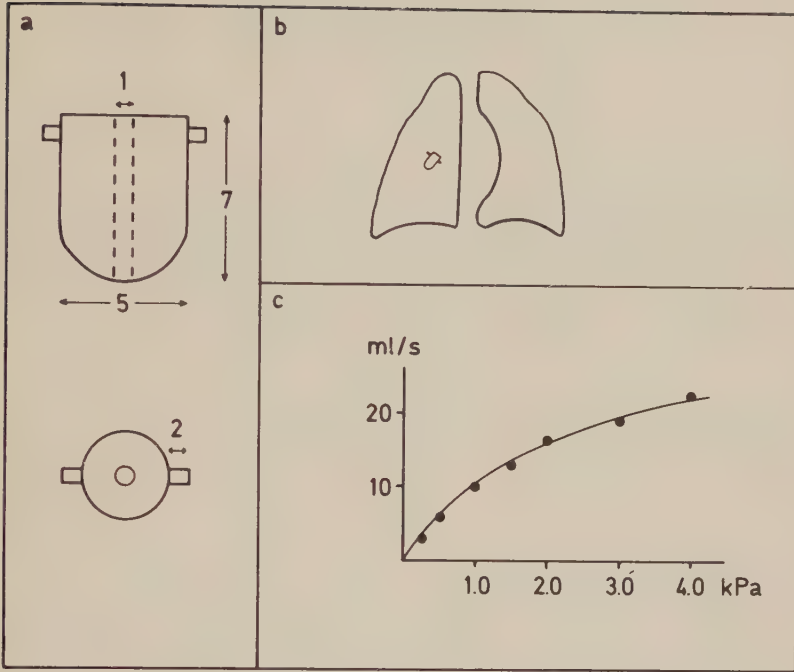


Fig. 2. a. Metal cylinder for regional bronchial obstruction. b. The cylinder in position. c. Flow resistance in the cylinder. Measures in mm.

After the completed investigation the animals were sacrificed and autopsied.

Mechanics of ventilation

Total compliance was calculated according to the formula

$$C_{TOT} = \frac{V_{T_{exp}}}{P_{ei}}$$

The tidal volume was set on the ventilator's dial. Leakage was prevented with a cuffed tracheal tube. The volume setting was controlled by the collection of expired gas in a Douglas' bag for 10 minutes. $V_{T_{exp}}$, corrected to BTPS, was calculated.

The tracheal pressures were recorded with electrodynamic pressure gauges (Siemens-Elema, EMT 34), amplifiers and ink-jet recorder (Siemens-Elema 81).

Gas analyses

The volume of expired O_2 and CO_2 was determined according to the method of SCHOLANDER (1947) from the gas sampled in the Douglas' bag. The respiratory quotient RQ was calculated according to the formula

$$RQ = \frac{\dot{V}_{CO_2}}{\dot{V}_{O_2}}$$

Arterial blood gases were measured with conventional electrodes (IL 213, Instrumentation Lab., USA). During the experiments the ventilation level was frequently controlled with an infra-red CO_2 analyser (Godhart, Holland) connected to an end-tidal sampler.

Physiological dead-space and alveolar ventilation

Physiological dead-space was calculated according to the formula

$$V_{D_{\text{phys}}} = \frac{P_a \text{CO}_2 - \bar{P}_E \text{CO}_2}{P_a \text{CO}_2 - P_I \text{CO}_2} \cdot V_{T_{\text{exp}}}$$

$V_{D_{\text{phys}}}$ includes the amount of gas, which is compressed in the connecting tubes so the alveolar ventilation was determined from the relationship:

$$V_A = V_{T_{\text{exp}}} - V_{D_{\text{phys}}}$$

Lung perfusion and gas distribution

Xe¹³³ radiospirometry was used for the determination of lung perfusion and gas distribution. The equipment and technique have previously been described by MIÖRNER (1968) with a modification of the collimators according to ARBORELIUS et al (1970). Four detectors were placed ventrally and four dorsally so that the lung volumes of four pulmonary fields were seen by the detectors (Fig. 1).

The animals examined were placed horizontally on their backs, fixed on a pillow which was filled with plastic balls. When the gas in the pillow was removed the pillow assumed a firm consistency (Vacuum immobilisator, Camp Scandinavia, Sweden). Through light sources on the detectors, luminous spots were marked out on the animals so that the initial position, if changed during examination, could be exactly reproduced.

Xe¹³³ has a low solubility in water and after injection into a central vein approximately 90 % of the gas is retained in the alveoli. The emitted gamma-radiation has two maximums, near 30 and 80 keV.

The discriminator of the equipment was set to accept radiation above 80 keV.

Approximately 0.2 mCi Xe^{133} dissolved in isotonic saline was injected through a catheter in the right atrium. Lung perfusion was measured during apnea from the maximum activity in each pulmonary field and expressed as a percentage. The actual field was related to the sum of the activity from all four lung fields according to

$$Q_{r_{LA}} \% = \frac{Q_{r_{LA}}}{Q_{r_{LA}} + Q_{r_{RA}} + Q_{r_{LB}} + Q_{r_{RB}}} \cdot 100$$

The regional ventilation in ml/min/ml of lung tissue was determined from the wash-out curves according to HECKSCHER et al (1966) and was expressed as a percentage of the total ventilation in all four pulmonary fields. The regional ventilation was expressed in ml/min/ml of lung according to the formula

$$V_r = \frac{e}{T \frac{1}{2}}$$

where e is the base for the natural logarithm and $T \frac{1}{2}$ is the half-time of the radionucleid in minutes, according to the same authors.

STATISTICS

Current statistical methods for mean values, standard deviation and standard error of the mean were used. Evaluation of the results was done with paired significance tests according to Student's t-test. ($\star = p < 0.05$, $\star\star = p < 0.01$, $\star\star\star = p < 0.001$).

PROCEDURES

After anaesthesia and the catheterization of the artery and vein the animals were intubated oro-tracheally. The position of the piglets in relation to the detectors was determined and the animals were fixed without interfering with the breathing movements.

Initially the ventilator's volume/pressure quotient was set at 20 ml/kPa. Normoventilation was set with the aid of a capnograph, and end-tidal sampling. The expired gas was collected in a Douglas' bag for 10 minutes. After 5 minutes arterial blood samples were taken for blood gas analyses and Xe^{133} was injected into a central vein. The ventilator was stopped during expiration for 10 seconds immediately after the injection of the radionucleid.

Pressures from the ventilator's pressure chamber, trachea, and the central vein were recorded. The same procedure was repeated with unchanged ventilation at a C_{vent} setting of 80 ml/kPa. Then the metal cylinder was inserted with the aid of a guide wire. The tidal volume was corrected to the initial value. Registration was carried out with C_{vent} 80 followed by C_{vent} 20 ml/kPa (Fig. 3).

After the completed investigation, all the animals were autopsied. The cranial lobe bronchus on the right side arose from the trachea approximately 1 cm proximal to the carina while a main bronchus was found on the left side. In all cases the position of the metal cylinder was in accordance with the radiographical documentation.

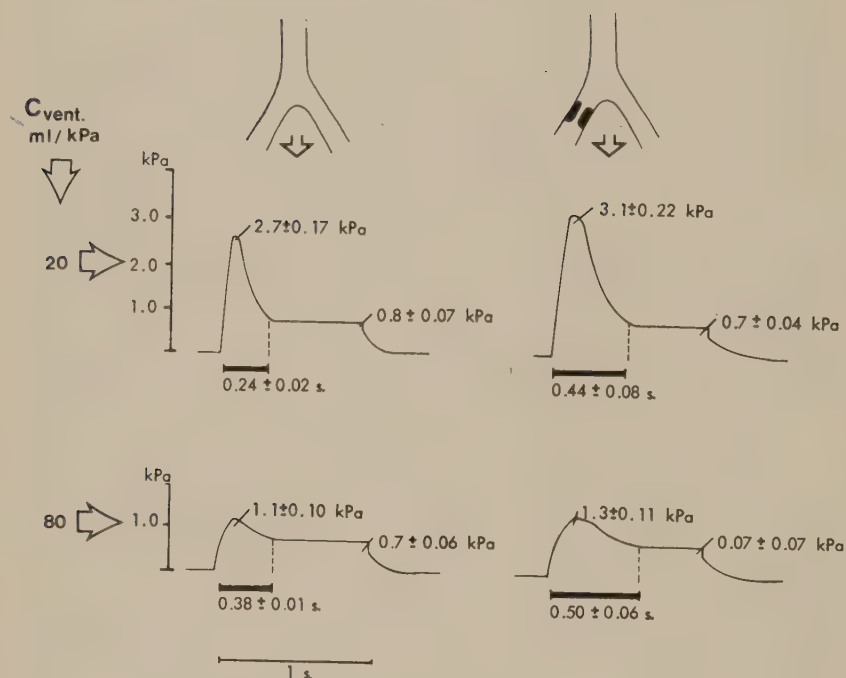


Fig. 3. Tracheal pressure profiles for the ventilatory volume/pressure quotients 20 and 80 ml/kPa in un-obstructed and bronchially obstructed airways. Mean values and standard error of the mean for P_{peak} , P_{ei} , t_{insuff} are presented.

TABLE 1. Mechanics of ventilation

	C_{vent}	P_{peak} kPa	P_{ei} kPa	t_{insuff} s.	t_{exsuff} s.	$V_{T_{vent}}$ ml	$V_{T_{exp}}$ ml	V_A ml	$V_{D_{phys}}/V_{T_{exp}}$	C_{TOT} ml/kPa
	20	2.7 ± 0.17 ★★ ★	0.8 ± 0.07	0.24 ± 0.02 ★ ★ ★	0.45 ± 0.05	86 ± 5.7	88 ± 5.6	37 ± 3.4	0.59 ± 0.02	119 ± 14.1
	80	1.1 ± 0.10	-59% 0.7 ± 0.06	-12% 0.38 ± 0.01	+58% 0.46 ± 0.06	86 ± 5.7	87 ± 7.8	35 ± 3.1	0.61 ± 0.01	122 ± 11.0
	20	3.1 ± 0.22 ★★ ★	0.7 ± 0.04	0.44 ± 0.08	0.32 ± 0.07	86 ± 6.3	91 ± 10.5	37 ± 3.8 ★	0.59 ± 0.02	120 ± 9.0
	80	1.3 ± 0.11	-58% 0.7 ± 0.07	$\pm 0\%$ 0.50 ± 0.06	+14% 0.36 ± 0.07	86 ± 6.3	86 ± 7.5	32 ± 3.6	0.63 ± 0.02	134 ± 13.4
	20	2.7 ± 0.17	0.8 ± 0.07	0.24 ± 0.02 ★	0.45 ± 0.05	86 ± 5.7	88 ± 5.6	37 ± 3.4	0.59 ± 0.02	119 ± 14.1
	20	3.1 ± 0.22	+15% 0.7 ± 0.04	-12% 0.44 ± 0.08	+83% 0.32 ± 0.07	86 ± 6.3	91 ± 10.5	37 ± 3.8	0.59 ± 0.02	120 ± 9.0
	80	1.1 ± 0.10	0.7 ± 0.06	0.38 ± 0.01	0.46 ± 0.06	86 ± 5.7	87 ± 7.8	35 ± 3.1	0.61 ± 0.01	122 ± 11.0
	80	1.3 ± 0.11	+18% 0.7 ± 0.07	$\pm 0\%$ 0.50 ± 0.06	+32% 0.36 ± 0.07	86 ± 6.3	86 ± 7.5	32 ± 3.6	0.63 ± 0.02	134 ± 13.4

RESULTS

Mechanics of ventilation (Table 1)

In un-obstructed airways and with C_{vent} at 20 the P_{peak} was 2.7 ± 0.17 kPa and with C_{vent} at 80 the P_{peak} was 1.1 ± 0.10 . The difference was significant ($p < 0.001$). The corresponding results for the duration of insufflation (t_{insuff}) was 0.24 ± 0.02 s, and 0.38 ± 0.01 s ($p < 0.001$, Fig. 2), respectively. The ex-sufflation time was not influenced.

After bronchial obstruction the P_{peak} rose to 3.1 ± 0.22 kPa with C_{vent} at 20 and to 1.3 ± 0.11 kPa with C_{vent} at 80. The corresponding t_{insuff} increased from 0.24 ± 0.02 s to 0.44 ± 0.08 s ($p < 0.05$) with C_{vent} at 20 and from 0.38 ± 0.01 s to 0.50 ± 0.06 s with C_{vent} at 80 (Fig. 3). The end-inspiratory tracheal pressure and the total compliance did not change when C_{vent} was changed from 20 to 80 ml/kPa, irrespective of un-obstructed or obstructed airways.

Gas analyses (Table 2)

In un-obstructed airways the difference between V_{Tvent} and V_{Texp} was negligible (2.3 %). With bronchial obstruction the difference increased to 5.8 % with a C_{vent} of 20.

With un-obstructed airways P_aO_2 , P_aCO_2 , pH, and RQ were not significantly influenced by changes in C_{vent} .

The CO_2 production was, on the other hand, on the average 5 % smaller with a C_{vent} of 80 than with a C_{vent} of 20.

After regional bronchial obstruction the P_aCO_2 decreased on average 8 % ($p < 0.05$) with C_{vent} at 20. pH rose, both with C_{vent} of 20 and 80 ml/kPa. The CO_2 production following bronchial obstruction with C_{vent} at 20 was on average 33 ± 4.2 ml/min and with a C_{vent} of 80 ml/kPa 28.8 ± 3.4 ml/min, which represented a 13 % difference ($p < 0.05$). However, there were no significant mutual differences recorded between the average for P_aCO_2 and pH with similar airway relationships and different C_{vent} .

TABLE 2. Gas exchange

	C_{vent}	pH	P_{aCO_2} kPa	P_{aO_2} kPa	$\dot{V}_{CO_2}$ ml/min	$\dot{V}_{O_2}$ ml/min	RQ
	20	7.41 ± 0.03	5.5 ± 0.20	12.2 ± 0.30	35.2 ± 3.6 *	40.4 ± 4.3	0.88 ± 0.04
	80	7.42 ± 0.03	5.6 ± 0.28 $\pm 0\%$	12.1 ± 0.46 -1%	33.3 ± 3.5 -5%	38.7 ± 3.7 -3%	0.86 ± 0.03 -2%
	20	7.47 ± 0.03	5.1 ± 0.27	12.5 ± 0.52 *	33.0 ± 4.2 *	38.0 ± 4.6	0.86 ± 0.04 *
	80	7.48 ± 0.03 $\pm 0\%$	5.2 ± 0.28 $\pm 0\%$	11.5 ± 0.49 -8%	28.8 ± 3.4 -13%	38.8 ± 4.7 $+2\%$	0.75 ± 0.06 -13%
	20	7.41 ± 0.03 *	5.5 ± 0.20 *	12.2 ± 0.30	35.2 ± 3.6	40.0 ± 4.3	0.88 ± 0.04
	20	7.47 ± 0.03 $+1\%$	5.1 ± 0.27 -8%	12.5 ± 0.52 $+2\%$	33.0 ± 4.2 -6%	38.0 ± 4.6 -5%	0.86 ± 0.04 -2%
	80	7.42 ± 0.03 *	5.6 ± 0.28 *	12.1 ± 0.46	33.3 ± 3.5 *	38.7 ± 3.7	0.86 ± 0.04 *
	80	7.48 ± 0.03 $+1\%$	5.2 ± 0.28 -7%	11.5 ± 0.49 -5%	28.8 ± 3.4 -14%	38.8 ± 4.7 $\pm 0\%$	0.75 ± 0.06 -13%

The mean P_aO_2 after bronchial obstruction was significantly lower ($p < 0.01$) with a C_{vent} of 80 than with a C_{vent} of 20, using otherwise unchanged ventilatory setting. O_2 -consumption was not changed by the different C_{vent} setting, yet the mean for RQ with C_{vent} at 80 ml/kPa was 13 % lower than with C_{vent} at 20 ml/kPa ($p < 0.01$).

The physiological dead-space and alveolar ventilation (Table 1)

With un-obstructed airways the V_{Dphys}/V_{Texp} ratio rose on average by 3 % and the alveolar ventilation decreased by 5 % when C_{vent} of 20 ml/kPa was changed to C_{vent} of 80. The difference in the V_{Dphys}/V_{Texp} ratio and alveolar ventilation was not statistically significant.

Bronchial obstruction increased the V_{Dphys}/V_{Texp} ratio on average by 7 % and decreased the alveolar ventilation on average by 14% ($p < 0.05$) during a change from a C_{vent} of 20 to a C_{vent} of 80.

Gas distribution (Table 3)

With un-obstructed airways and a C_{vent} of 20 the bases of the lungs were better ventilated and the apices of the lungs a little less well ventilated than with C_{vent} at 80. The difference in the ventilation of the bases between a C_{vent} of 20 and a C_{vent} of 80 was, on average, 9.8% for the right base, and 11.7% for the left base. The difference was not statistically significant.

After bronchial obstruction ventilation of the obstructed region was decreased at both C_{vent} settings. The reduction with C_{vent} at 20 was 24.1 % ($p < 0.01$) and 21.9 % with C_{vent} at 80 ($p < 0.05$). For the un-obstructed base region the ventilation with a C_{vent} of 20 was reduced by 14.9 % ($p < 0.05$) while there was an increase of 8.3 % in the same region with a C_{vent} of 80. The ventilation

TABLE 3. Regional pulmonary ventilation (Vr)

	C _{vent}	RA	LA	RE	LB
	20	19.3 ^{+2.4}	16.6 ^{+2.5}	31.9 ^{+2.7}	34.3 ^{+2.0}
	80	20.1 ^{+3.0}	+4.1% 20.8 ^{+2.3}	+25.3% 28.8 ^{+3.5}	-9.8% 30.3 ^{+1.5} -11.7%
	20	25.5 ^{+2.8}	★ ★ 21.1 ^{+1.2}	24.2 ^{+2.1}	29.2 ^{+1.4} ★
	80	23.2 ^{+3.1}	-9.0% 21.5 ^{+2.8}	+1.9% 22.5 ^{+2.4}	-7.0% 32.8 ^{+2.2} +12.3%
	20	19.3 ^{+2.4}	★ ★ 16.6 ^{+2.5}	31.9 ^{+2.7} ★ ★	34.3 ^{+2.0} ★
	20	25.5 ^{+2.8}	+32.1% 21.1 ^{+1.2}	+27.1% 24.2 ^{+2.1}	-24.1% 29.2 ^{+1.4} -14.9%
	80	20.1 ^{+3.0}	20.8 ^{+2.3}	28.8 ^{+3.5} ★	30.3 ^{+1.5}
	80	23.2 ^{+3.1}	+15.4% 21.5 ^{+2.8}	+3.4% 22.5 ^{+2.4}	-21.9% 32.8 ^{+2.2} +8.3%

fraction increased by 32.1 % ($p < 0.01$) in the right apical lung region and by 27.1 % in the left apical lung region with a C_{vent} of 20. The increase in the ventilation fraction in both apical regions was less with a C_{vent} of 80 and was calculated to be 15.4 % for the right apical region and 3.4 % for the left apical region.

Lung perfusion (Table 4)

With un-obstructed airways the perfusion was even. There was no significant difference between the settings of C_{vent} at 20 or 80.

With regional bronchial obstruction there was a minor increase of lung perfusion by 7.1 % in the obstructed lung segment at a C_{vent} of 80. The increase in perfusion was not statistically significant.

DISCUSSION

Measurements of mechanical data were planned with a view to a careful definition of the ventilatory conditions for a comparison of the two volume/pressure ratios C_{vent} 20 and C_{vent} 80. The primary question was how gas distribution and lung perfusion were influenced by the two ventilatory patterns both with un-obstructed airways and with regional bronchial obstruction.

A volumetrically equal tidal volume was delivered both at a C_{vent} of 20 and 80 ml/kPa. The insufflation time was about 60 % shorter with a C_{vent} of 20 than of 80 (LINDAHL & OKMIAN 1977 b). The shorter time could be due to the fact that when a C_{vent} of 20 was used, the presumptive tidal volume was compressed in a pressure chamber of only 1/4 of the size for a C_{vent} of 80. The pressure in the chamber with a C_{vent} of 20, i.e. the energy required to carry out an inspiration, was significantly higher, compared to when the C_{vent} was set at 80. This relationship was reflected in the size of the corresponding tracheal peak pressures, 2.7 ± 0.17 kPa and

TABLE 4. Regional pulmonary perfusion (Qr)

	C _{vent}	RA	LA	RB	LB
	20	15.9 [±] 2.6%	15.3 [±] 1.4%	31.4 [±] 1.8%	37.4 [±] 3.2%
	80	16.5 [±] 2.7%	+3.8% 15.2 [±] 1.6%	-1% 29.7 [±] 0.8%	-5% 38.6 [±] 4.3%
	20	17.2 [±] 3.1%	14.4 [±] 0.9%	31.1 [±] 2.1%	37.4 [±] 3.8%
	80	17.2 [±] 2.6%	±0% 14.5 [±] 1.2%	+0.7% 31.8 [±] 2.7%	+2.3% 36.6 [±] 3.2%
	20	15.9 [±] 2.6%	15.3 [±] 1.4%	31.4 [±] 1.8%	37.4 [±] 3.2%
	20	17.2 [±] 3.1%	+8.2% 14.4 [±] 0.9%	-5.9% 31.1 [±] 2.1%	-1.0% 37.4 [±] 3.8%
	80	16.5 [±] 2.7%	15.2 [±] 1.6%	29.7 [±] 0.8%	38.6 [±] 4.3%
	80	17.2 [±] 2.6%	+4.2% 14.5 [±] 1.2%	-4.6% 31.8 [±] 2.7%	+7.1% 36.6 [±] 3.2%
					-5.2%

1.1 ± 0.10 kPa. With regional airway obstruction the tracheal peak pressures were increased but the insufflation times were lengthened.

From earlier observations it was concluded that during artificial ventilation the time required to reach pressure equilibrium between the trachea and the alveoli reflected the effectiveness of the ventilator (LINDAHL & OKMIAN 1977 b). Thus during artificial ventilation of the same lungs using different ventilators, the duration of insufflation provides a measure of the ventilator's efficiency. The results with airway obstruction in this investigation showed that when the performance of the ventilator is known, the duration of insufflation provides possibilities for the evaluation of the conditions within the airways and lungs.

On the basis of the time factors for the C_{vent} settings investigated, it was also possible to calculate the approximate corresponding maximum ventilatory frequencies. For example, at a C_{vent} of 20 and an inspiration of 33 % of the breathing cycle, the maximum frequency was about 80 cycles/minute and with a C_{vent} at 80 it was about 50 cycles/minute. If these frequencies are exceeded a completed insufflation of the tidal volume is not fulfilled and its size is reduced.

The possibilities of influencing the length of the insufflation time raised the question of whether gas distribution and lung perfusion were influenced by the size of the tracheal peak pressure and insufflation time, i.e. whether some of the C_{vent} settings used led to a better ventilation and a more effective gas transport than the other, even when regional bronchial obstruction was present.

Airway resistance and the time constant for the right base were increased by inserting a metal cylinder in the right lower lobe bronchus (time constant = airway resistance $\cdot$ compliance). The induced resistance was measured at approximately 0.12 to 0.15 kPa/ml/s. With a pressure of 3.1 kPa (C_{vent} 20) a maximum of 21 ml/s of breathing gas could pass the obstruction and with a pressure of 1.3 kPa (C_{vent} 80) the maximum was 13 ml/s. In both instances the results represented approximately 10 % of the total gas transport in a free airway. The rendered regional bronchial obstruction was substantial.

According to BALL et al (1962) the greatest error, using radiospirometry, is a change in the position of the animal in relation to the detectors. With the piglet in a horizontal position, the possibility of reproducing the initial position, after changes during the examination, are most favourable. This view is shared by WEST et al (1960), who also showed that a horizontal position, with spontaneous breathing, reduced the gravity-dependent differences in lung perfusion and gas distribution between apical and basal pulmonary lobes.

One way of keeping the animals in a horizontal and unchanged position was to use a special bottom layer, another was to mark the position of the animals by luminous spots from the detectors.

Determination of static lung volumes with re-breathing of Xe^{133} is, according to KETY (1951), not necessary. In this study the exhalation was so long that even the obstructed region should reach the functional residual capacity and unchanged lung volume ascertained. The wash-out of the nucleid from the pulmonary fields is a function of ventilatory efficiency within the area, that is to say, it describes regional pulmonary ventilation. Accordingly the measurements showed relative changes in ventilation and perfusion at different ventilatory settings within four pulmonary fields. With un-obstructed airways, no important changes in P_aO_2 and P_aCO_2 were measured when ventilation at a C_{vent} of 20 was compared to a C_{vent} of 80. Somewhat higher CO_2 production was shown at a C_{vent} of 20, on the other hand the O_2 consumption was also higher, so RQ remained unchanged.

However, with obstructed airways alveolar ventilation, RQ and P_aO_2 were increased at a C_{vent} of 20 compared to those at a C_{vent} of 80 (Table 4). Similar results have previously been published by OWEN-THOMAS et al (1968) using high flow rates and inspiration fractions of 1:4 and 1:5 during artificial ventilation of neonates with hyaline membrane disease.

With free airways no significant differences in gas distribution were shown between C_{vent} 20 and 80. Yet there was a tendency to more efficient ventilation of the caudal lobes at a C_{vent} of 20, while the reverse occurred in the cranial lobes. A hypothetical explanation may be that the high energy insufflation at a C_{vent} of 20 accelerated the inert visceral contents relatively more than the low energy delivered by C_{vent} 80 ml/kPa.

The introduction of the regional obstruction, however, changed this pattern of distribution. A significant decrease in regional ventilation could be seen in the obstructed lobe. Sufficient time constants at both C_{vent} settings made the ventilatory difference small between C_{vent} 20 and 80. Besides, the ventilation of the contralateral base also decreased with a C_{vent} of 20. A compensatory increased ventilation was seen in the apical regions at both C_{vent} settings.

If total compliance is regarded as a mean value of the compliance for various pulmonary regions, we are allowed to assume that the total compliance of different regions is dependent on the space available for pulmonary excursion. In these conditions a shorter insufflation time, with a C_{vent} of 20 will expand un-obstructed pulmonary regions more rapidly. This would reduce both the excursion of the obstructed pulmonary region and its apparent total compliance. The compensatory hyperventilation of the apical pulmonary fields could be explained in the same way, i.e. that the shorter insufflation time for the apical region is due to the morphology of the airways. Their caudal movement is not restrained as is the case with the basal ones due to abdominal inertia. The more favourable ventilatory conditions for the apical, pulmonary fields influenced the gas distribution to a major extent, especially at a C_{vent} of 20.

The intention and basis for the construction of different C_{vent} settings of 20, 40, etc on the TVM-ventilator were to achieve a suitable volume pressure quotient for different sizes of patients. The sensitivity of the differential pressure manometers in controlling the volume measurements allowed an equally safe volume measurement at a C_{vent} of 80 as at 20 ml/kPa when tidal volumes of 10 and 15 ml in preterm neonates should be set.

The results from this investigation have shown that access to several C_{vent} settings are of restricted value. Evidently large C_{vent} settings offer advantages, such as even gas distribution and low initial tracheal peak pressure, without any obvious disadvantages. The difference in calculated maximal ventilatory frequency at C_{vent} 80 and 20 ml/kPa is of no practical importance as these frequencies are higher than those commonly used. Only at the extremes, such as low compliant lungs in hyaline membrane disease and at ventilatory frequencies of over 50 cycles/minute are there possible indications for the use of a C_{vent} of 20 ml/kPa.

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EXPERIMENTAL STUDIES ON ARTIFICIAL
VENTILATION USING THE TVM-VENTILATOR
IV. Duration of inspiration, pulmonary
ventilation, gas distribution, and lung
perfusion

STEN LINDAHL, MÅNS ARBORELIUS J:r and LUDVIG OKMIAN

From the Department of Paediatric Surgery, University Hospital,
S-221 85 Lund, and the Department of Clinical Physiology,
Malmö General Hospital, S-214 01 Malmö, Sweden

Short running title: TVM-ventilator - Duration of inspiration,
pulmonary ventilation, gas distribution, and lung perfusion

ABSTRACT

Tidal volumes of the same magnitude and at the same ventilatory frequency were delivered to piglets during anaesthesia with muscle relaxation using the TVM-ventilator (Tidal Volume Monitoring) set for a short (10 %) and a long (33 %) duration of inspiration (10 %, simulating pressure-controlled ventilation, and 33 % giving ordinary volume-controlled ventilation) with un-obstructed airways and after bronchial obstruction. The evaluation of ventilation was carried out by mechanical data, quantitative analysis of expired gas, blood gas analyses and Xe^{133} radiospirometry.

By interruption of the insufflation before pressure equilibrium between the ventilator and the individual was established (10 % inspiration) a higher P_{peak} and P_{ei} and a lower C_{TOT} were measured compared to those at 33 % inspiration.

With simulated pressure-controlled ventilation (10 % inspiration) and regional bronchial airway obstruction, V_A and $V_{D_{\text{anat}}}$ were reduced while the $V_{D_{\text{phys}}}/V_{T_{\text{exp}}}$ ratio was increased in comparison with volume-controlled ventilation (33 % inspiration).

With a short inspiration (10 %) and a higher P_{peak} the cranial pulmonary fields were better ventilated while the right caudal field was less well ventilated due to abdominal inertia.

It was true that the pressure-controlled ventilation could bring about an adequate alveolar ventilation but V_A was reduced with bronchial obstruction and an increase in dead-space ventilation was recorded. As a steady state during artificial ventilation, especially in neonates, hardly exists, except for short periods, a volumetrical control of pulmonary ventilation is preferred.

The choice between pressure- and volume-controlled artificial ventilation has been a subject for debate for decades, especially as regards methods and apparatus for artificial ventilation in young individuals. Pressure-controlled ventilation is characterized by an interrupted insufflation as the preset tracheal pressure level is reached, irrespective of lung expansion. Consequently, an end-tidal gas flow exists, so tidal volume and mechanics of ventilation expressed as total compliance cannot be estimated without special electronic equipment scarcely suitable in clinical practice. In extreme circumstances it may even be difficult or almost impossible to decide whether the ventilator delivers any pulmonary ventilation at all, or whether ventilation is limited to tubing and humidifiers. However, in spite of these drawbacks, several authors advocate pressure-controlled ventilation in children (REYNOLDS 1964, TUNSTALL et al 1968, and others).

Volume-controlled ventilation has been accepted as the method of choice in artificial ventilation of adults. An argument often referred to for the rare use of this method also in children is the technical difficulties of measuring small tidal volumes. A controversial question concerning volume-controlled ventilation is whether ventilation with or without an endo-tracheal pressure plateau (i.e. a short phase in the end of the inspiration without a pressure gradient between the ventilator and the airways of the individual) should be preferred or not. SABAR et al (1965) found experimentally that the static end-inspiratory phase gave time for redistribution and compensation for the differences in time constants between obstructed and un-obstructed parts of the lungs. MEIER & BAUM (1976) on the other hand, showed that pendelluft and re-breathing were the consequences of the plateau phase.

The TVM-ventilator (Tidal Volume Monitoring, OKMIAN 1973, OKMIAN et al 1974, LINDAHL & OKMIAN 1977 a, b) widened the means for studies of specific endo-tracheal pressure profiles. The ventilator is volume-controlled and time-cycled but it can also to some extent simulate the characteristics of a pressure-controlled apparatus.

This investigation includes mechanics of ventilation, gas exchange, gas distribution and lung perfusion with simulated pressure-controlled and ordinary volume-controlled ventilation with a plateau-phase using equal tidal volumes at the same ventilatory frequency. Registration of the parameters mentioned were carried out both on un-obstructed airways and after regional bronchial obstruction.

MATERIAL

Six piglets of the Swedish native breed were investigated on six occasions. Their body weights were between 7 and 12 kg (mean 10.3 kg).

SYMBOLS

b.w.	Body weight, (kg),
C_{TOT}	Total compliance, (ml/kPa),
C_{vent}	Ventilator volume/pressure quotient, (ml/kPa),
f	Ventilatory frequency, (cycles/minute),
LA	Left pulmonary apex,
LB	Left pulmonary base,
P_aCO_2	Arterial carbon dioxide tension, (kPa),
$\bar{P}_E CO_2$	Mean partial pressure of carbon dioxide in mixed expired gas, (kPa),
P_{ei}	End-inspiratory tracheal pressure, (kPa),
$P_{ET} CO_2$	End-tidal carbon dioxide tension, (kPa),
$P_I CO_2$	Partial pressure of carbon dioxide in inspired air, (kPa),
P_{peak}	Tracheal peak pressure, (kPa),
Qr	Regional pulmonary perfusion, (percentage of total pulmonary perfusion),
RA	Right pulmonary apex,
RB	Right pulmonary base,

RQ	Respiratory quotient,
t_{exsuff}	Duration of exsufflation, (s),
t_{insuff}	Duration of insufflation, (s),
V_A	Alveolar ventilation, (ml),
$\dot{V}_{\text{CO}_2}$	Carbon dioxide production, STPD, (ml/min),
$V_{D_{\text{alv}}}$	Alveolar dead-space, (ml),
$V_{D_{\text{anat}}}$	Anatomical dead-space, (ml),
V_{D_c}	External dead-space (compressed gas in tubing), (ml),
$V_{D_{\text{phys}}}$	Physiological dead-space, (ml),
$\dot{V}_{\text{O}_2}$	Oxygen consumption, STPD, (ml/min),
V_r	Regional pulmonary ventilation, (percentage of total pulmonary ventilation),
$V_{T_{\text{exp}}}$	Tidal volume, expired gas corrected to BTPS, (ml),
$V_{T_{\text{vent}}}$	Tidal volume, read on the ventilator's dial, (ml).

METHODS

The simulated pressure-controlled curve profile was achieved by interrupting the insufflation after 0.3 s (inspiration 10 % of the entire breathing cycle). An endo-tracheal pressure plateau was obtained with an inspiration time of 1 s (inspiration 33 % of the breathing cycle). During all investigations ventilation was carried out with a ventilatory frequency of 20 cycles/minute and a ventilatory volume/pressure quotient of 40 ml/kPa.

The experimental set up and equipment is shown in Fig. 1. A complete description of the method used has previously been reported (LINDAHL et al 1977 a). Regional bronchial obstruction was induced by a metal cylinder (I.D. = 1 mm), which was inserted into the right caudal lobe bronchus. The flow resistance of the cylinder is shown graphically in Figure 2. The exact location was checked during fluoroscopy and documented by photographs before and after registration and also at the following autopsy.

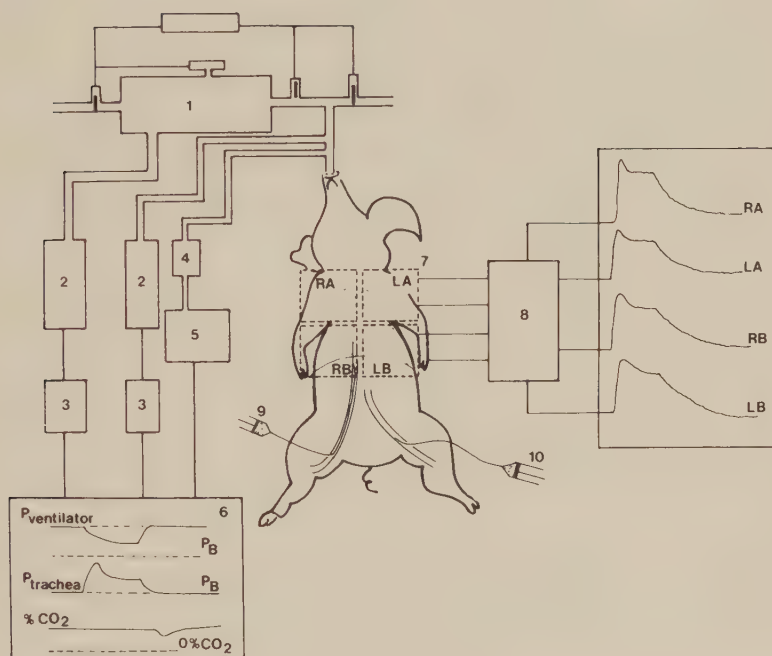


Fig. 1. Schematic presentation of the experimental set up and the method. 1/ The TVM-ventilator with its pressure chamber, PC, valves and electronics. 2/ Pressure gauges. 3/ Amplifiers. 4/ End-tidal sampler. 5/ Infra-red carbon dioxide analyser. 6/ Recorder. 7/ Detectors for radiospirrometry. 8/ Computer and printer-plotter. 9/ Central venous catheter. 10/ Arterial catheter.

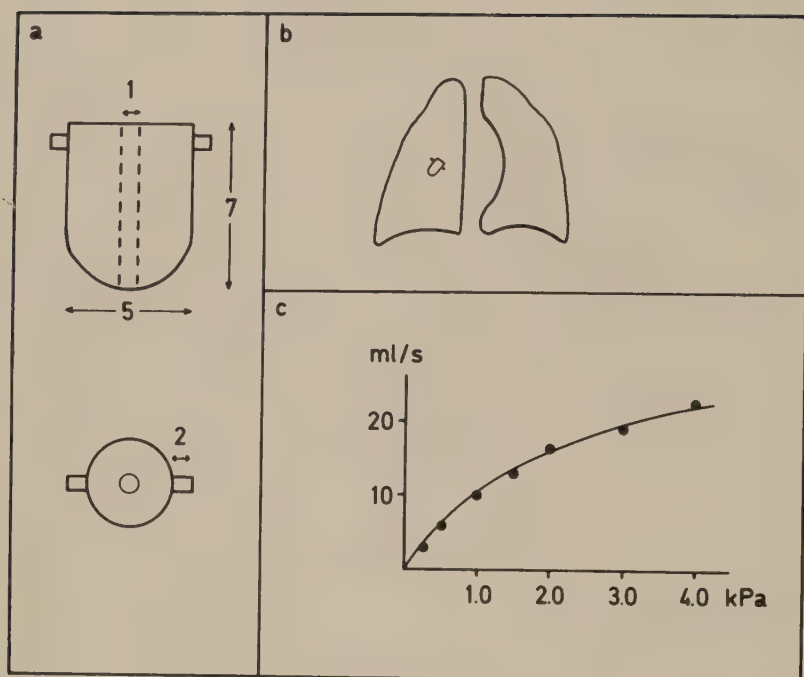


Fig. 2. a. Metal cylinder for regional bronchial obstruction. b. The cylinder in position. c. Flow resistance in the cylinder. Measures in mm.

A combination of Dridol (Droperidolum INN) 1 - 2 mg/kg b.w. and Ketalar (Ketaminum NFN) 30 - 50 mg/kg b.w. intramuscularly was used as anaesthetic agent. Alloferin (Alcuronum NFN) 1 - 2 mg was injected intravenously when needed for muscle relaxation. In the whole series the animals were ventilated with air.

Gas pressures were registered with conventional electrodynamic pressure gauges, amplifiers and ink-jet recorder (Siemens-Elema EMT 34, EM 81). Ventilation was frequently checked by an infra-red CO₂ analyser (Godhart, Holland), connected to an end-tidal sampler. Arterial blood gases were analysed by conventional electrode systems (IL 213, Instrumentation Lab., USA). Expired gas was sampled for a period of 10 minutes and analysed according to SCHOLANDER (1947). The tidal volume calculated from these analyses contained the tidal volume of gas that left the ventilator's pressure chamber including the compressed gas volume in the tubing between the ventilator and the individual (V_{D_c} ml). V_{D_c} was in all examinations 10 ml/kPa. By the aid of gas analyses $\dot{V}_{\text{CO}_2}$ and $\dot{V}_{\text{O}_2}$ as well as RQ were also calculated.

V_{D_{phys}} (including the amount of breathing gas that left the ventilator's pressure chamber without being involved in gas exchange) was calculated according to the formula

$$V_{D_{\text{phys}}} = \frac{P_a \text{CO}_2 - \bar{P}_E \text{CO}_2}{P_a \text{CO}_2 - P_I \text{CO}_2} \cdot V_{T_{\text{exp}}}$$

the anatomical dead-space according to the formula

$$V_{D_{\text{anat}}} = \frac{P_{ET} \text{CO}_2 - \bar{P}_E \text{CO}_2}{P_{ET} \text{CO}_2 - P_I \text{CO}_2} \cdot V_{T_{\text{exp}}}$$

and the alveolar dead-space according to the formula

$$V_{D_{\text{alv}}} = V_{D_{\text{phys}}} - V_{D_{\text{anat}}} - V_{D_c}$$

Xe¹³³ radiospirometry was used for the determination of lung perfusion and gas distribution according to a method described by MIÖRNER (1968) and modified by ARBORELIUS et al (1970). Four pulmonary fields were seen by four pairs of detectors placed ventrally and dorsally. The distribution of perfusion was measured from the maximal activity in each pulmonary field during apnea and was expressed as a percentage of the total pulmonary activity.

Regional ventilation was estimated from the wash-out curves and expressed as a percentage of the summated ventilation in all four pulmonary fields.

Current statistical methods for mean values, standard deviation and standard error of the mean were used. Evaluation of the results was done with paired significance tests according to Student's t-test (★ = $p < 0.05$, ★ ★ = $p < 0.01$, ★ ★ ★ = $p < 0.001$)

PROCEDURE

After induction of anaesthesia and catheterization of an artery and a vein the animals were intubated orotracheally. The position of the piglets in relation to the detectors was fixed and could be reproduced exactly with the aid of luminous spots, which were marked out on the animals.

With an inspiration fraction of 10 % of the whole breathing cycle and a ventilatory frequency of 20 cycles/minute, normoventilation was achieved with the aid of a capnograph. Thereafter expired gas was collected in a Douglas' bag for 10 minutes. After 5 minutes an arterial blood sample was taken and Xe¹³³ radionucleid was injected into a central vein, followed by apnea for 10 s. Registration of pressures from a central vein, the pressure chamber of the ventilator and from the trachea were made simultaneously.

The same readings were repeated with 33 % inspiration time using the same ventilatory frequency and tidal volume. The metal cylinder was then inserted into the right caudal lobe bronchus by a guide wire. Pulmonary ventilation of the same magnitude as before the regional obstruction was then continued and recordings were performed again in the same way as described earlier.

All the animals were autopsied. In all of them the bronchus to the cranial right pulmonary lobe arose from the trachea approximately 1 cm proximal to the carina. The position of the cylinder was always in accordance with that shown by fluoroscopy and by radiographs taken during the investigations.

RESULTS

In 2 of the 6 animals satisfactory position for the cylinder was not obtained. Accordingly the results of bronchial obstruction were only based on 4 examinations, and comparison before and after bronchial obstruction could only be carried out in the 4 cases successfully obstructed.

Mechanics of ventilation and gas analyses

Complete data for mechanics of ventilation and gas analyses are presented in Figure 3, and Tables 1 and 2.

With a duration of inspiration of 10 % (simulated pressure-controlled ventilation), C_{TOT} was significantly reduced both with free airways ($p < 0.01$) and with bronchial obstruction ($p < 0.05$) in comparison with an inspiration of 33 % (Table 1).

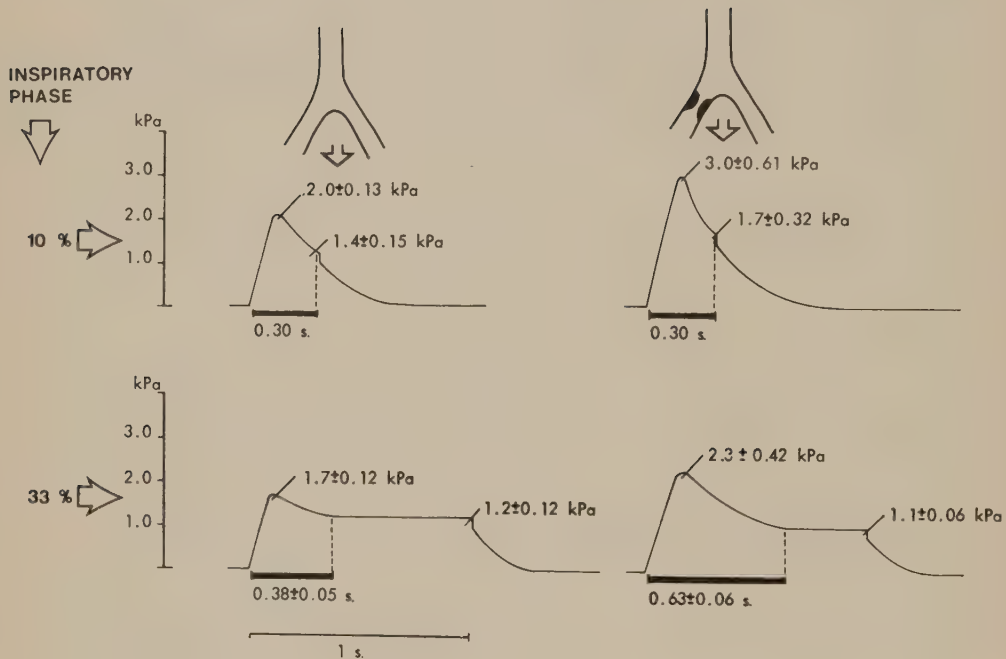


Fig. 3. Tracheal pressure profiles for durations of inspirations 10 and 33 % with un-obstructed airways and after bronchial obstruction. Mean values and standard error of the mean for P_{peak} , t_{insuff} , and P_{ei} are presented.

n	% in- spir.	P _{peak} kPa	P _{ei} kPa	t _{insuff} s.	t _{exsuff} s.	V _{T_{exp}} ml	C _{TOT} ml/kPa	
	6	10	2.0 [±] 0.13 ★	1.4 [±] 0.15 ★	0.30 [±] 0	0.38 [±] 0.08	124 [±] 21.8	88.5 [±] 6.4 ★ ★
	33	33	1.7 [±] 0.12 -15%	1.2 [±] 0.12 -14%	0.38 [±] 0.05 +27%	0.41 [±] 0.07 +8%	129 [±] 21.2 +4%	100.5 [±] 7.6 +14%
	4	10	3.0 [±] 0.61 ★	1.7 [±] 0.32	0.30 [±] 0	0.30 [±] 0.05	108 [±] 19.9	63.5 [±] 3.7 ★
	33	33	2.3 [±] 0.42 -23%	1.1 [±] 0.06 -35%	0.63 [±] 0.06 +110%	0.44 [±] 0.07 +47%	108 [±] 24.3 ±0	101.0 [±] 9.6 +59%
	4	10	2.0 [±] 0.12	1.2 [±] 0.06	0.30 [±] 0	0.38 [±] 0.08	101 [±] 9.0	92.1 [±] 9.1
	10	10	3.0 [±] 0.61 +50%	1.7 [±] 0.32 +42%	0.30 [±] 0 ±0	0.30 [±] 0.05 -21%	108 [±] 19.9 +7%	63.5 [±] 3.7 -31%
	4	33	1.6 [±] 0.13	1.0 [±] 0.06	0.39 [±] 0.06 ★	0.41 [±] 0.07	113 [±] 27.3	103.6 [±] 10.0
	33	33	2.3 [±] 0.42 +44%	1.1 [±] 0.06 +10%	0.63 [±] 0.06 +62%	0.44 [±] 0.07 +7%	108 [±] 24.3 -4%	101.0 [±] 9.6 -3%

TABLE 2. Gas exchange

n	% in- spir.	pH	P _a CO ₂ kPa	P _a O ₂ kPa	$\dot{V}_{CO_2}$ ml/min	$\dot{V}_{O_2}$ ml/min	RQ					
	6	10	7.42 ^{+0.03}	5.7 ^{+0.19}	10.7 ^{+0.74}	★	47.9 ^{+7.2}	55.0 ^{+7.2}	0.85 ^{+0.06}	★		
	33	7.43 ^{+0.04}	±0%	5.7 ^{+0.24}	±0%	11.0 ^{+0.80}	+3%	51.2 ^{+8.1}	53.8 ^{+7.3}	-2%	0.94 ^{+0.07}	+11%
	4	10	7.41 ^{+0.05}	6.1 ^{+0.25}	★	10.4 ^{+0.73}		44.7 ^{+5.6}	54.4 ^{+4.6}		0.80 ^{+0.04}	
	33	7.43 ^{+0.05}	±0%	5.7 ^{+0.30}	-7%	10.9 ^{+0.82}	+5%	47.2 ^{+5.3}	53.5 ^{+3.1}	-2%	0.88 ^{+0.06}	+10%
	4	10	7.41 ^{+0.05}	5.8 ^{+0.27}		10.8 ^{+1.06}		40.5 ^{+3.9}	48.8 ^{+4.3}		0.80 ^{+0.07}	
	10	7.41 ^{+0.05}	±0%	6.1 ^{+0.25}	+5%	10.4 ^{+0.73}	-4%	44.7 ^{+5.6}	54.4 ^{+4.6}	+11%	0.80 ^{+0.04}	±0%
	4	33	7.42 ^{+0.06}	5.7 ^{+0.37}		11.3 ^{+1.1}		44.6 ^{+9.2}	50.8 ^{+8.4}		0.86 ^{+0.04}	
	33	7.43 ^{+0.05}	±0%	5.7 ^{+0.30}	±0%	10.9 ^{+0.82}	-4%	47.2 ^{+5.3}	53.5 ^{+3.1}	+5%	0.88 ^{+0.06}	+2%

Dead-space and alveolar ventilation

Recorded and calculated values are presented in Table 3. The size of V_{Dphys} did not show any significant differences with free airways or with bronchial obstruction when inspiration times of 10 and 33 % were compared. The ratio V_{Dphys}/V_{Texp} was lower with an inspiration time of 33 % than of 10 %, both with free airways and with bronchial obstruction ($p < 0.05$). At the same time the V_{Danat} showed lower values with an inspiration time of 33 % and with regional bronchial obstruction ($p < 0.05$). V_{Dalv} increased considerably with an inspiration time of 10 % ($p < 0.001$). At 33 % only a minor increase was registered. V_{Danat} , on the other hand, was insignificantly reduced before and after bronchial obstruction with an inspiration time of 10 % while a considerable decrease was found at 33 %.

Gas distribution

With free airways both cranial pulmonary fields were better ventilated with an inspiration time of 10 % than with 33 %. In the right caudal lobe the ventilation was lower at 10 % than at 33 %. In the left caudal lobe no differences were seen (Table 4).

With regional bronchial obstruction ventilation was reduced by 5 % in the obstructed caudal lobe when 10 % inspiration time was compared to 33 %. The differences were not significant.

Lung perfusion

With free airways a decreased perfusion in the right caudal lobe was registered when 10 % was compared to 33 % ($p < 0.05$). The changes in the other pulmonary fields were infinitesimal (Table 5).

With regional bronchial obstruction the perfusion increased to a minor extent in the obstructed area, both with 10 % and 33 % inspiration times. This increase was compensated for by a comparative decrease in the perfusion of the contralateral caudal

TABLE 3. Alveolar ventilation and dead - space.

n	% in- spir.	$V_{D_{phys}}$ ml	V_{D_c} ml	$V_{D_{anat}}$ ml	$V_{D_{alv}}$ ml	$V_{D_{phys}}/V_{T_{exp}}$	V_A ml
	10	75 ± 9.9	14 ± 1.6	★	26 ± 4.0	0.63 ± 0.02	46 ± 8.5
33	68 ± 10.8	-9%	12 ± 1.2	-14%	32 ± 5.0	0.59 ± 0.02	50 ± 10.0
	10	70 ± 12.2	18 ± 3.2				
33	63 ± 6.3	-10%	11 ± 0.6	-39%	36 ± 5.2	0.66 ± 0.02	44 ± 6.7
	10	63 ± 4.8	12 ± 0.8				
33	70 ± 12.2	+11%	18 ± 3.2	+50%	35 ± 8.2	0.59 ± 0.03	51 ± 7.5
	10	60 ± 10.8	11 ± 0.9				
33	63 ± 6.3	+5%	11 ± 0.6	-0%	32 ± 7.3	0.61 ± 0.02	48 ± 11.5
	10	63 ± 6.3	11 ± 0.6				
33	63 ± 6.3	+5%	11 ± 0.6	-46%	35 ± 8.2	0.59 ± 0.03	51 ± 7.5

TABLE 4. Regional pulmonary ventilation, (Vr).

	n	% in- spir	RA	LA	RB	LB
	6	10	20.6 ^{+1.0}	21.2 ^{+2.9}	25.2 ^{+1.7}	33.0 ^{+1.4}
	33		19.0 ^{+1.7}	-8% 19.3 ^{+1.8}	-9% 28.6 ^{+1.8}	33.9 ^{+2.1} +3%
	4	10	24.4 ^{+1.1}	22.0 ^{+0.7}	23.7 ^{+1.9}	29.9 ^{+2.0}
	33		19.4 ^{+2.8}	-20% 23.7 ^{+2.0}	+8% 24.9 ^{+1.4}	32.0 ^{+2.0} +7%
	4	10	20.9 ^{+1.5}	19.6 ^{+3.2}	26.2 ^{+2.1}	33.4 ^{+1.5}
	10		24.4 ^{+1.1}	+17% 22.0 ^{+0.7}	+12% 23.7 ^{+1.9}	29.9 ^{+2.0} -10%
	4	33	19.3 ^{+2.6}	18.5 ^{+0.9}	30.2 ^{+2.4}	32.0 ^{+1.1}
	33		19.4 ^{+2.8}	+1% 23.7 ^{+2.0}	+28% 24.9 ^{+1.4}	32.0 ^{+2.0} +0%

TABLE 5. Regional pulmonary perfusion, (QR).

n	% in- spir.	RA	LA	RB	LB				
	6	10	18.8 $\pm$ 1.6	18.6 $\pm$ 1.3	30.1 $\pm$ 2.1	★	32.5 $\pm$ 2.4		
	33	18.5 $\pm$ 1.9	-2%	17.8 $\pm$ 1.0	-4%	31.5 $\pm$ 1.8	+5%	32.3 $\pm$ 2.6	-1%
	4	10	20.1 $\pm$ 2.1	★	15.8 $\pm$ 1.5	35.2 $\pm$ 4.8	28.9 $\pm$ 3.1	★	
	33	18.1 $\pm$ 2.0	-10%	16.4 $\pm$ 0.9	+4%	34.0 $\pm$ 3.2	-3%	31.5 $\pm$ 3.0	+9%
	4	10	18.8 $\pm$ 2.2	16.6 $\pm$ 0.8	31.1 $\pm$ 2.8	33.5 $\pm$ 3.7			
	10	20.1 $\pm$ 2.1	+7%	15.8 $\pm$ 1.5	-5%	35.2 $\pm$ 4.8	+13%	28.9 $\pm$ 3.1	-14%
	4	33	18.1 $\pm$ 2.6	16.5 $\pm$ 0.7	32.4 $\pm$ 2.2	33.0 $\pm$ 4.1			
	33	18.1 $\pm$ 2.0	+0%	16.4 $\pm$ 0.9	-1%	34.0 $\pm$ 3.2	+5%	31.5 $\pm$ 3.0	-5%

lobe. A better perfusion was recorded in the right cranial area ($p < 0.05$) with an inspiration time of 10 % compared to 33 %.

DISCUSSION

The ventilator used (OKMIAN 1973) consists of a rigid-walled pressure chamber and electromagnetic valves. Already at the beginning of an inspiration the breathing gas is compressed within the pressure chamber at a fixed pressure level. When the inspiratory valve opens the pressure in the pressure chamber decreases proportionally to the amount of gas leaving the chamber. The pressure in the airways raises rapidly and a maximal airway pressure, i.e. initial tracheal peak pressure, is reached within approximately 0.1 s. Lung expansion in the ventilator-patient-system is brought about by the pressure gradient. With equilibration of pressure and static conditions in the ventilator-patient-system (plateau phase), insufflation of the tidal volume is terminated. The functional principle of the TVM-ventilator is to be classified as a decelerating flow ventilator according to MUSHIN et al (1969).

The simulated pressure-controlled ventilation was attained by an interruption of the insufflation before equilibration of pressure was established. This was achieved by setting the inspiration time at 0.3 s. With volume-controlled ventilation (i.e. static end-inspiratory conditions), the inspiration time was set at 1.0 s. Equilibration of pressure occurred after 0.38 ± 0.05 s in unobstructed airways and after 0.63 ± 0.06 s with bronchial obstruction. This meant that the airways of the animal were exposed to the same tracheal pressure-profile under the compared ventilatory conditions. This procedure must be regarded as advantageous when comparing pressure- and volume-controlled ventilators with different tracheal profiles.

It is obvious that significantly higher P_{peak} and P_{ei} were recorded with simulated pressure-controlled ventilation (Table 1), since end-tidal conditions with continuous inspiratory gas flow include

a pressure gradient which is proportional to the gas flow. To reach these end-tidal conditions a greater pressure gradient between the ventilator and the airways was required, which also was reflected by the higher initial tracheal peak pressure.

These circumstances also explain the lower C_{TOT} with simulated pressure-controlled ventilation even if the term C_{TOT} at continuous end-tidal gas flow is inadequate.

No dramatic differences in dead-space and alveolar ventilation were shown when pressure- and volume-controlled ventilation were compared with free airways. The higher mean value for V_{DC} with simulated pressure-controlled ventilation was due to the higher end-tidal pressure. This change in V_{DC} also explained the calculated change in the V_{Dphys}/V_{Texp} ratio.

However, with bronchial airway obstruction alveolar ventilation was essentially reduced with simulated pressure-controlled ventilation while it remained unchanged using volume-controlled ventilation. Pulmonary ventilation using a longer duration of inspiration and volume-controlled ventilation was shown to be more efficient than with a higher pressure gradient and simulated pressure-controlled ventilation. The V_{Dphys}/V_{Texp} ratio was increased with bronchial obstruction and pressure-controlled ventilation (Table 3). This was related to a reduction by more than 40 % of the $V_{D_{anat}}$ with volume-controlled ventilation and indicated an increased ventilation of the dead-space with pressure-controlled ventilation.

The radiospirometric investigation of gas distribution and lung perfusion could, in many respects, be related to the course of events in the examined ventilatory profiles. The more efficient ventilation of the cranial pulmonary fields with simulated pressure-controlled ventilation could probably be related to the greater initial tracheal pressure gradient between the ventilator and the airways (LINDAHL et al 1977 a). Under the same conditions a less efficient ventilation in the right caudal pulmonary field could be explained by a reduced lung excursion due to inertia of the abdominal organs.

However, with bronchial airway obstruction, the reduced ventilation in the obstructed field was insignificant when the two tracheal pressure profiles were compared. The increased perfusion within the obstructed area indicated a lower alveolar pressure level than in un-obstructed areas. This hypothesis is supported by WEST's (1974) description of the interaction between alveolar and capillar pressure in different pulmonary regions.

BERGMAN (1967) claimed that the endo-tracheal pressure profiles during artificial ventilation was of minor importance if only adequate alveolar ventilation could be attained at the different pressure profiles. BERGMAN used only a pressure-controlled ventilator in his investigation. The reduction in alveolar ventilation with regional obstruction and the increased dead-space ventilation measured in our investigation are parameters not considered by BERGMAN in his report, but of uttermost importance if regional time constants (OTIS et al 1956) increase as in most lung disease. With high constants, high driving pressures will have to be used in pressure controlled ventilation, so that lung rupture in less obstructed areas is a substantial risk. With the present system the driving pressure falls when the lungs are expanded and less energy is left for causing lung rupture in the end of inspiration (KIRKPATRICK et al 1974, OGATA et al 1976).

In this connection it is important to note that steady state during artificial ventilation of neonates hardly exists, except for short periods. It was true that pressure-controlled ventilation could bring about an adequate alveolar ventilation, but without a volumetrical control of the course of events. Hence, pressure-controlled ventilation of neonates must be condemned.

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EXPERIMENTAL STUDIES ON ARTIFICIAL
VENTILATION USING THE TVM-VENTILATOR

V. Ventilatory frequency, pulmonary
ventilation, gas distribution and lung
perfusion

STEN LINDAHL, MÅNS ARBORELIUS J:r and LUDVIG OKMIAN

From the Department of Paediatric Surgery, University Hospital,
S-221 85 Lund, and the Department of Clinical Physiology,
Malmö General Hospital, S-214 01 Malmö, Sweden

Short running title: TVM-ventilator - Ventilatory frequencies,
pulmonary ventilation, gas distribution and lung perfusion

ABSTRACT

Five piglets of the Swedish native breed were artificially normoventilated using ventilatory frequencies of 10.3 and 30 cycles/minute. Mechanics of ventilation, gas distribution, gas exchange, and lung perfusion were recorded with normal airways and after experimental induction of bronchial obstruction.

A ventilatory frequency of 10.3 cycles/minute required twice as large a tidal volume as 30 cycles/minute. These volumes resulted in end-inspiratory tracheal pressures of 1.7 and 0.76 kPa, respectively.

In- and exsufflation of tidal volumes at $f = 30$ demanded 70 - 75 % of the time required for the transport of larger tidal volumes at $f = 10.3$

Thus, normoventilation at low ventilatory frequencies could be obtained without dangerous tracheal pressure levels, even with regional bronchial obstruction, in species whose normal spontaneous breathing frequency is high. At high frequency a large proportion of the inhaled gas was "wasted" due to increased dead-space ventilation.

The $V_{D_{phys}}/V_{T_{exp}}$ ratio was greater at $f = 30$ than at $f = 10.3$ cycles/minute. This could be related to a significant increase in the $V_{D_{anat}}/V_{T_{exp}}$ ratio at $f = 30$, while the $V_{D_C}/V_{T_{exp}}$ and $V_{D_{alv}}/V_{T_{exp}}$ were unchanged at both frequencies. In other words, the increased amount of gas required to ventilate the non- CO_2 producing parts of the ventilatory system (animal + tubing) at $f = 30$ cycles/minute, was extensively due to an increased anatomical dead-space ventilation.

Paradoxically the exsufflation time with both frequencies and with regional bronchial obstruction was shorter than with an un-obstructed airway, which could be, however, explained by a compensatory hyperdistention of the un-obstructed pulmonary fields.

Fourfield radiospirometry revealed, gas distribution and lung perfusion to be even at both frequencies, with un-obstructed airways. With regional bronchial obstruction and $f = 30$, the regional ventilation and perfusion within the obstructed pulmonary field were reduced to some extent compared to the same values at $f = 10.3$ cycles/minute. This was explained by air trapping.

During artificial ventilation the tidal volume is determined by the choice of ventilatory frequency and consequently the endotracheal end-inspiratory pressure. At operation, the basis for this choice in neonates and small infants, with their high spontaneous breathing frequencies, is still under debate. However, low ventilatory frequencies during surgery offer comfortable conditions in the operating field and perhaps also ventilatory advantages.

This experimental investigation deals with physiological pulmonary data of interest for the choice of ventilatory frequency during artificial ventilation in young individuals. Special interest was paid to mechanics of ventilation, gas exchange, gas distribution, and lung perfusion with un-obstructed airways and with regional bronchial obstruction. In previous publications (LINDAHL et al 1977 a, b) the ventilatory effects of different tracheal peak pressures and duration of inspiration at the same ventilatory frequency and minute ventilation, have been investigated. In this series ventilatory frequency and minute ventilation corresponding to adequate gas exchange constituted the premises.

MATERIAL

Five piglets of the Swedish native breed were used in the investigation. The body weights were between 7 and 9 kg (mean 7.9 kg).

SYMBOLS

b.w.	Body weight, (kg),
C_{TOT}	Total compliance, (ml/kPa),
C_{vent}	Ventilator volume/pressure quotient, (ml/kPa),
f	Ventilatory frequency, (cycles/minute),

LA	Left pulmonary apex,
LB	Left pulmonary base,
$P_a\text{CO}_2$	Arterial carbon dioxide tension, (kPa),
$P_{A-a}\text{O}_2$	Alveolo-arterial oxygen difference, (kPa),
P_B	Atmospheric pressure, (kPa),
$\bar{P}_E\text{CO}_2$	Mean partial pressure of carbon dioxide in mixed expired gas, (kPa),
P_{ei}	End-inspiratory tracheal pressure, (kPa),
$P_{ET}\text{CO}_2$	End-tidal carbon dioxide tension, (kPa),
$P_I\text{CO}_2$	Partial pressure of carbon dioxide in inspired air, (kPa),
P_{peak}	Tracheal peak pressure, (kPa),
Qr	Regional pulmonary perfusion, (percentage of total pulmonary perfusion),
RA	Right pulmonary apex,
RB	Right pulmonary base,
RQ	Respiratory quotient,
t_{exsuff}	Duration of exsufflation, (s),
t_{insuff}	Duration of insufflation, (s),
V_A	Alveolar ventilation, (ml),
$\dot{V}_A$	Alveolar minute ventilation, (l/min),
$\dot{V}_{\text{CO}_2}$	Carbon dioxide production, STPD, (ml/min),
$V_{D\text{alv}}$	Alveolar dead-space, (ml),
$V_{D\text{anat}}$	Anatomical dead-space, (ml),
V_{Dc}	External dead-space (compressed gas in tubing), (ml),
$V_{D\text{phys}}$	Physiological dead-space, (ml),
$\dot{V}_E$	Expired minute ventilation corrected to BTPS, (l/min),
$\dot{V}_{\text{O}_2}$	Oxygen consumption, STPD, (ml/min),
Vr	Regional pulmonary ventilation (percentage of total pulmonary ventilation),
$V_{T\text{exp}}$	Tidal volume corrected to BTPS, (ml),
$V_{T\text{vent}}$	Tidal volume, read on the ventilator's dial, (ml).

METHODS

Curarized animals with and without experimentally induced regional bronchial obstruction were normoventilated at ventilatory frequencies 12 and 30 cycles/minute. Pulmonary ventilation, i.e. mechanical data, gas exchange, gas distribution, and lung perfusion, were compared at the two frequencies (Fig. 1).

The TVM-ventilator was used (OKMIAN 1973, OKMIAN et al 1974). The volume/pressure quotient of the ventilator, i.e. the internal compliance of the ventilator, was 40 ml/kPa.

Normoventilation was maintained at the two frequencies by following the expired end-tidal CO_2 -fraction. As a criterion for normoventilation $P_{\text{ET}}\text{CO}_2$ was held within the range 5 - 5.6 kPa.

Irrespective of the ventilatory frequency, the same intrapulmonary pressure time per inspiration was used. This meant a duration of inspiration, at $f = 12$, of 20 % and at $f = 30$ of 50 %. These inspiration times both corresponded to a duration of 1 s.

Regional airway obstruction was obtained by a metal cylinder (I.D. = 1 mm). This was inserted into the right caudal lobe bronchus. Its resistance is shown graphically in Figure 2. The position of the cylinder was controlled by fluoroscopy and documented photographically before and after measurements and finally confirmed at autopsy of the animal. Methods and apparatus are schematically shown in Figure 1.

A combination of Dridol (Droperidolum INN) 1 - 2 mg/kg b.w. and Ketalar (Ketaminum NFN) 30 - 50 mg/kg b.w. injected intramuscularly was used as anaesthetic agent. For muscle relaxation Alloferin (Alcuronum NFN) in doses of 1 - 2 mg was injected intravenously when needed. During all investigations room air without any added gases was used.

Gas pressures were measured by electrodynamic pressure gauges, amplifiers, and ink-jet recorder (Siemens-Eléma EMT 34, EM 81). The ventilatory level was frequently controlled during the inves-

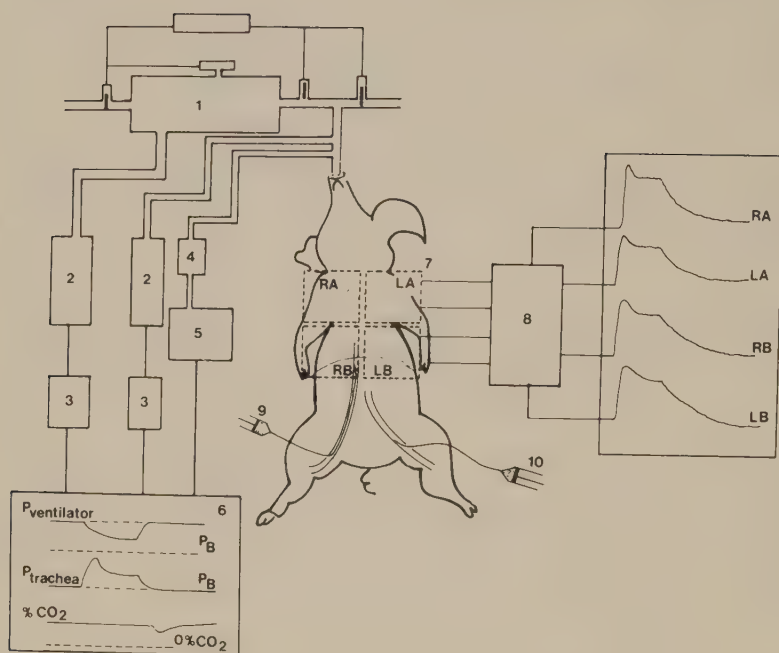


Fig. 1. Experimental design and method. 1/ The TVM-ventilator with pressure chamber, valves and electronics. 2/ Pressure gauges. 3/ Amplifiers. 4/ End-tidal sampler. 5/ Infra-red CO₂ analyser. 6/ Ink-jet recorder. 7/ Detectors for radiospirometry. 8/ Computer and printer-plotter. 9/ Central venous catheter. 10/ Arterial catheter.

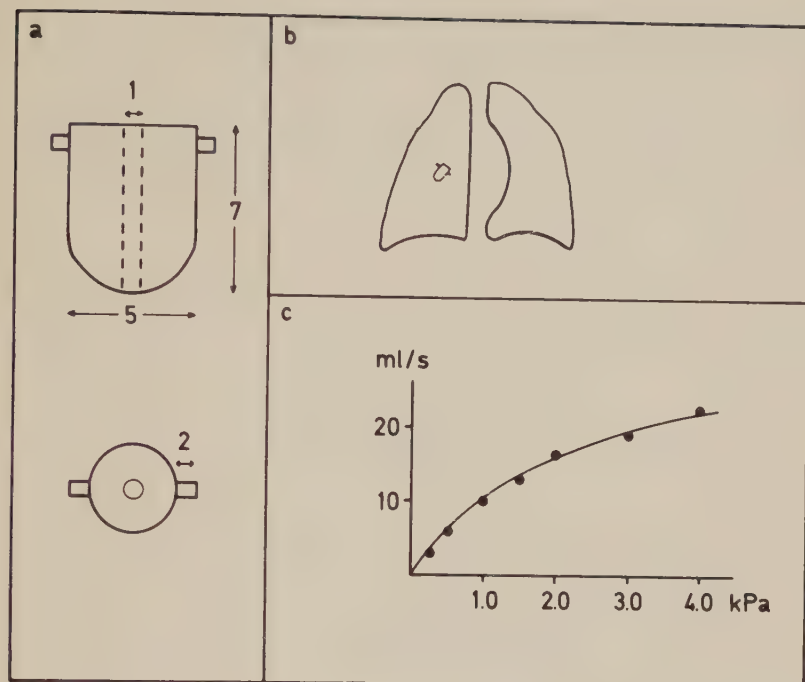


Fig. 2. a. Metal cylinder for obstruction of the regional bronchus. b. Position of the metal cylinder. c. Flow resistance through the metal cylinder. Measures in mm.

tigations with an end-tidal sampler connected to an infra-red CO₂ analyser (Godhart, Holland). Arterial blood gases were analysed with conventional electrodes (IL 213, Instrumentation Lab., USA). Expired 10 minute gas volumes were sampled in a Douglas' bag and analysed according to SCHOLANDER (1947). The volume of gas collected was the sum of the animal's expired gas together with the compressible volume of the tubing. The latter was regarded as an external dead-space (V_{DC} ml) within the physiological dead-space. V_{DC} was, in all the investigations, 10 ml/kPa. $\dot{V}_{CO_2}$, $\dot{V}_{O_2}$ and RQ were calculated from analyses of the expired gas volumes.

The physiological dead-space was calculated according to the formula

$$V_{D_{phys}} = \frac{P_aCO_2 - \bar{P}_E CO_2}{P_aCO_2 - P_I CO_2} \cdot V_{T_{exp}}$$

The anatomical dead-space was calculated according to the formula

$$V_{D_{anat}} = \frac{P_{ET}CO_2 - \bar{P}_E CO_2}{P_{ET}CO_2 - P_I CO_2} \cdot V_{T_{exp}}$$

The alveolar dead-space was calculated by the formula

$$V_{D_{alv}} = V_{D_{phys}} - V_{D_{anat}} - V_{D_C}$$

Xe¹³³ radiospirometry according to MIÖRNER (1968) and modified after ARBORELIUS et al (1970) was used for the determination of gas distribution and lung perfusion. Four pulmonary fields were seen by four pairs of detectors placed ventrally and dorsally (LINDAHL et al 1977).

Regional lung perfusion was measured from the maximum activity in each pulmonary field during apnea lasting 10 seconds and was expressed as the percentage of total pulmonary perfusion going to each field.

Regional pulmonary ventilation was determined from the wash-out curves and expressed as a percentage of the total pulmonary ventilation.

Current methods for mean values, standard deviation and standard error of the mean were used. Evaluation of the results was done with paired significance tests according to Student's t-test ($\star = p < 0.05$, $\star\star = p < 0.01$, $\star\star\star = p < 0.001$).

PROCEDURE

After induction of anaesthesia and catheterization of the femoral artery and vein the animals were intubated orotracheally. The position of the animals in relation to the detectors was fixed and marked out so that the exact position could be reproduced.

At a ventilatory frequency of 12 cycles/minute and a duration of inspiration of 20 %, normoventilation was obtained by end-tidal sampling and momentary infra-red CO_2 analyses. Expired gas was sampled in a Douglas' bag for 10 minutes. After 5 minutes an arterial blood sample was taken for analysis and Xe^{133} was rapidly injected into a central vein, followed by 10 second's apnea. Thereafter, pressures in the central vein, the ventilator's pressure chamber, and in the trachea were measured.

The same procedure was repeated at $f = 30$ cycles/minute and a duration of inspiration of 50 % at the same ventilatory level.

The metal cylinder was then inserted into the right caudal lobe bronchus with the aid of a guide wire.

External ventilation was adjusted until end-tidal CO_2 stabilized at the same value as before and the recordings were repeated.

All the animals were autopsied. In all the piglets the bronchus to the right cranial lobe arose from the trachea approximately 1 cm proximal to the carina.

RESULTS

On checking the readings it was seen that the ventilatory frequencies used were in fact 10.3 and 30 cycles/minute instead of 12 and 30 cycles/minute. Consequently the duration of inspiration at $f = 10.3$ then became 1.16 s and the tidal volume somewhat larger compared to $f = 12$. However, the prerequisite conditions for the comparison, i.e. unchanged alveolar ventilation at the two ventilatory frequencies, were fulfilled (Table 3).

Mean values, standard error of mean and evaluation of statistical data for mechanics of ventilation are presented in Table 1 and Figure 3, and those for gas exchange in Tables 2, 3, 4 and 5. Regional gas distribution and lung perfusion determined by Xe^{133} radiospirometry are shown in Tables 6 and 7.

With un-obstructed airways and with obstruction of a regional bronchus significantly lower tracheal peak pressures and end-inspiratory tracheal pressures were measured at $f = 30$ compared to those at $f = 10.3$ cycles/minute.

The duration of both in- and exsufflation was significantly shorter at $f = 30$ compared to that at $f = 10.3$ cycles/minute both with un-obstructed and with an obstructed regional bronchus. A shorter duration of exsufflation at both frequencies was found with obstructed as compared to un-obstructed airways.

Neither at $f = 10.3$ nor at $f = 30$ cycles/minute could any change in minute ventilation be measured when the regional bronchus was obstructed. Arterial blood gases, $\dot{V}_{\text{CO}_2}$ and RQ were unchanged at the two frequencies, while the $P_{\text{A-aO}_2}$ difference was significantly lower at $f = 10.3$ than at $f = 30$ ($p < 0.05$).

With un-obstructed airways and $f = 10.3$ cycles/minute the alveolar minute ventilation was 0.74 ± 0.08 l/min compared to 0.80 ± 0.08 l/min at $f = 30$ cycles/minute. On the other hand the alveolar ventilation breath by breath was 60 % larger at $f = 10.3$ than at $f = 30$ cycles/minute ($p < 0.001$, Table 3).

TABLE 1. Data for mechanics of ventilation in five piglets before and after obstruction of the bronchus.

f	P _{peak} kPa	P _{ei} kPa	$\dot{V}_E$ l/min	V _{Texp} ml	t _{insuff} s.	t _{exsuff} s.	C _{TOT} ml/kPa
 10.3	3.4 [±] 0.31	★ ★ ★	★ ★ ★	★ ★	★ ★	★ ★	★ ★
 30	1.6 [±] 0.13	-53%	1.66 [±] 0.12	158 [±] 11.2	0.45 [±] 0.05	0.64 [±] 0.07	98.0 [±] 9.3
			2.35 [±] 0.16	78 [±] 5.2	-51%	0.45 [±] 0.04	-30%
				+42%	-18%		104.1 [±] 7.3 +6%
 10.3	3.5 [±] 0.45	★ ★ ★	★ ★ ★	★ ★	★ ★	★ ★	★ ★
 30	1.8 [±] 0.29	-49%	1.52 [±] 0.11	148 [±] 11.0	0.94 [±] 0.11	0.46 [±] 0.06	85.3 [±] 6.2
			2.26 [±] 0.15	73 [±] 4.8	-49%	0.30 [±] 0.02	-35%
				+49%	-29%		81.6 [±] 8.1 -4%
 10.3	3.4 [±] 0.31		★				
 10.3	3.5 [±] 0.45	+3%	1.65 [±] 0.12	158 [±] 11.2	0.45 [±] 0.05	0.64 [±] 0.07	98.0 [±] 9.3
			1.52 [±] 0.11	148 [±] 11.0	0.94 [±] 0.11	0.46 [±] 0.06	-28%
				-8%	-6%		85.3 [±] 6.2 -13%
 30	1.6 [±] 0.13		0.76 [±] 0.04	78 [±] 5.2	0.37 [±] 0.03	0.45 [±] 0.04	104.1 [±] 7.3
 30	1.8 [±] 0.29	+13%	2.26 [±] 0.15	73 [±] 4.8	0.67 [±] 0.05	0.30 [±] 0.02	-33%
				-4%	-6%		81.6 [±] 8.1 -22%

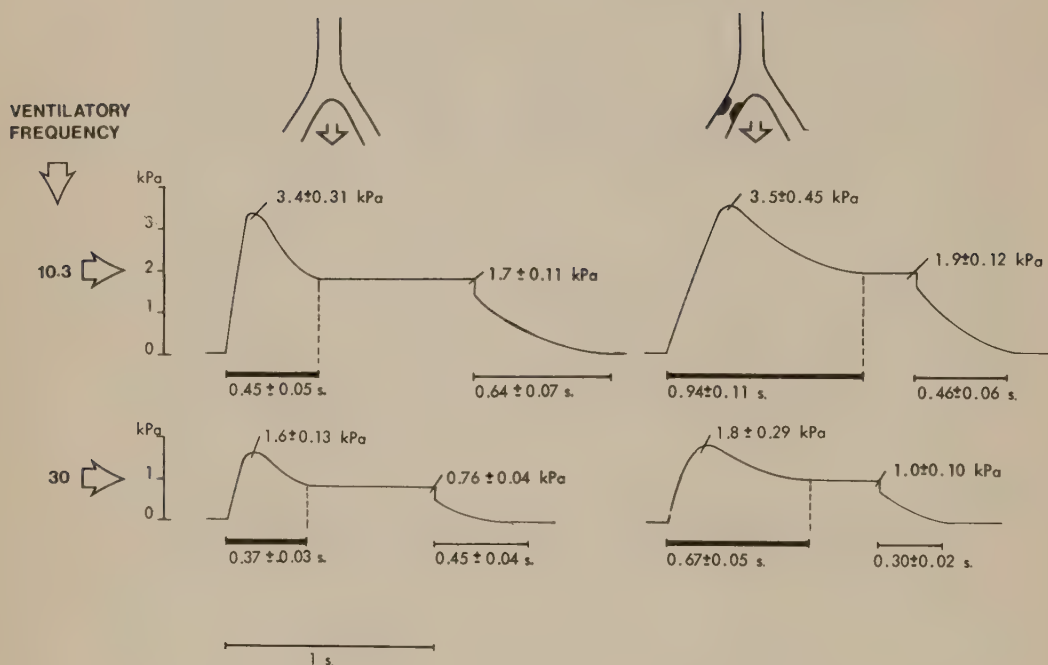


Fig. 3. Tracheal pressure profile at $f = 10.3$ and $f = 30$ cycles/minute before and after bronchial obstruction.

TABLE 2. Gas exchange in five piglets before and after obstruction of the bronchus.

f	pH	P _a CO ₂ kPa	P _a O ₂ kPa	$\dot{V}_{CO_2}$ ml/min	$\dot{V}_{O_2}$ ml/min	RQ	P _{A-a} O ₂ kPa						
	10.3	7.47 ^{+0.04}	5.4 ^{+0.33}	11.2 ^{+0.52}	34.0 ^{+2.8}	41.2 ^{+2.9}	0.82 ^{+0.02}	2.2 ^{+0.37}					
30	7.50 ^{+0.03}	^{+0%} 5.3 ^{+0.21}	-2%	11.7 ^{+0.49}	+4%	37.4 ^{+3.6}	+10%	43.7 ^{+3.0}	+6%	0.85 ^{+0.04}	+4%	2.1 ^{+0.55}	-5%
	10.3	7.47 ^{+0.04}	5.6 ^{+0.38}	11.3 ^{+0.69}	32.0 ^{+1.6}	38.8 ^{+2.6}	0.83 ^{+0.02}	1.9 ^{+0.61} ★					
30	7.48 ^{+0.03}	^{+0%} 5.3 ^{+0.22}	-5%	10.4 ^{+0.77}	-8%	34.9 ^{+2.6}	+9%	41.0 ^{+2.4}	+6%	0.85 ^{+0.02}	+2%	3.1 ^{+0.95}	+63%
	10.3	7.47 ^{+0.04}	5.4 ^{+0.33}	11.2 ^{+0.52}	34.0 ^{+2.8}	41.2 ^{+2.9}	0.82 ^{+0.02}	2.2 ^{+0.37}					
10.3	7.47 ^{+0.04}	^{+0%} 5.6 ^{+0.38}	+4%	11.3 ^{+0.69}	+1%	32.0 ^{+1.6}	-6%	38.8 ^{+2.6}	-6%	0.83 ^{+0.02}	+1%	1.9 ^{+0.61}	-14%
	30	7.50 ^{+0.03}	5.3 ^{+0.21}	11.7 ^{+0.49}	37.4 ^{+3.6}	43.7 ^{+3.0}	0.85 ^{+0.04}	2.1 ^{+0.55}					
30	7.48 ^{+0.03}	-1%	5.3 ^{+0.22}	^{+0%} 10.4 ^{+0.77}	-11%	34.9 ^{+2.6}	-7%	41.0 ^{+2.4}	-5%	0.85 ^{+0.02}	^{+0%} 3.1 ^{+0.95}	+48%	

TABLE 3. Physiological dead-space and alveolar ventilation in five piglets before and after obstruction of the bronchus.

f	$V_{D_{phys}}$ ml	$V_{D_{phys}}$ l/min	V_A ml	$\dot{V}_A$ l/min	$V_{D_{phys}}/V_T$ exp
 10.3 30	86^{+6}_{-3}	★ ★ 0.89 $\pm$ 0.06 -42% 1.50 $\pm$ 0.10	★ ★ 72 $\pm$ 7 27 $\pm$ 3	★ ★ ★ 0.74 $\pm$ 0.08 0.80 $\pm$ 0.08	0.55 $\pm$ 0.02 +8% 0.65 $\pm$ 0.02 ★ ★ ★ +18%
 10.3 30	82^{+9}_{-2}	★ 0.84 $\pm$ 0.08 -41% 1.44 $\pm$ 0.06	★ ★ ★ 84 $\pm$ 20 28 $\pm$ 5	★ 0.67 $\pm$ 0.06 0.71 $\pm$ 0.08	0.56 $\pm$ 0.03 +6% 0.67 $\pm$ 0.02 ★ ★ +20%
 10.3 10.3	86^{+6}_{-9}	0.89 $\pm$ 0.06 -5% 0.84 $\pm$ 0.08	72 $\pm$ 7 84 $\pm$ 20	0.74 $\pm$ 0.07 0.67 $\pm$ 0.06	0.55 $\pm$ 0.02 -9% 0.56 $\pm$ 0.03 +2%
 30 30	50^{+3}_{-2}	1.50 $\pm$ 0.09 -4% 1.44 $\pm$ 0.06	27 $\pm$ 3 28 $\pm$ 5	0.80 $\pm$ 0.08 0.71 $\pm$ 0.08	0.65 $\pm$ 0.02 -11% 0.67 $\pm$ 0.02 +3%

TABLE 4. Dead-space volumes with un-obstructed airways in five animals.

f	$V_{D_{phys}}$ ml	V_{D_c} ml	$V_{D_{anat}}$ ml	$V_{D_{alv}}$ ml	
	10.3	86 ⁺⁶	★★ 18 ⁺¹	★★★ 27 ^{+4.0}	45 ⁺¹⁰ ★
	30	50 ⁺³	-42% 9 ⁺¹	-53% 26 ⁺⁴	-2% 21 ⁺⁵ -53%

TABLE 5. Different dead-space volumes in relation to $V_{T_{exp}}$ with un-obstructed airways in five animals.

f	$V_{D_{phys}}/V_{T_{exp}}$	$V_{D_c}/V_{T_{exp}}$	$V_{D_{anat}}/V_{T_{exp}}$	$V_{D_{alv}}/V_{T_{exp}}$
10.3	0.55 ^{+0.02}	★★★ 0.11 ^{+0.01}	0.16 ^{+0.03}	★★★ 0.25 ^{+0.04}
30	0.65 ^{+0.02}	+18% 0.10 ^{+0.01}	-9% 0.29 ^{+0.03}	+81% 0.23 ^{+0.05} -8%

TABLE 6. Regional pulmonary ventilation (in percentage of the total pulmonary ventilation) in five piglets before and after obstruction of the bronchus.

f	RA	LA	RB	LB
 10.3 30	26.3 ⁺¹ _{-1.1} 27.0 ⁺⁰ _{-0.8}	23.1 ⁺⁴ _{-2.1} 22.8 ⁺² _{-1.1}	21.0 ⁺² _{-2.7} 21.5 ⁺¹ _{-1.6}	29.6 ⁺² _{-2.0} 28.6 ⁺¹ _{-1.1} +3%
 10.3 30	29.0 ⁺² _{-2.4} 25.8 ⁺² _{-2.2}	★ 22.7 ⁺¹ _{-1.5} 25.5 ⁺³ _{-3.3}	20.0 ⁺² _{-2.0} 18.0 ⁺³ _{-3.9}	28.2 ⁺¹ _{-1.5} 30.6 ⁺¹ _{-1.7} +9%
 10.3 10.3	26.3 ⁺¹ _{-1.1} 29.0 ⁺² _{-2.4}	23.1 ⁺⁴ _{-2.2} 22.7 ⁺¹ _{-1.5}	21.0 ⁺² _{-2.7} 20.0 ⁺¹ _{-2.0}	29.6 ⁺² _{-2.0} 28.2 ⁺¹ _{-1.5} -5%
 30 30	27.0 ⁺⁰ _{-0.8} 25.8 ⁺² _{-2.2}	22.8 ⁺² _{-2.1} 25.5 ⁺³ _{-3.3}	21.5 ⁺¹ _{-1.6} 18.0 ⁺³ _{-3.9}	28.6 ⁺¹ _{-1.1} 30.6 ⁺¹ _{-1.7} +7%

TABLE 7. Regional pulmonary perfusion (in percentage of the total pulmonary perfusion) in five piglets before and after obstruction of the bronchus.

f	RA	LA	RB	LB
 10.3 30	20.8 $\pm$ 1.7 20.5 $\pm$ 2.0	17.8 $\pm$ 1.0 15.1 $\pm$ 1.0	★ ★ 33.6 $\pm$ 1.6 -15% 34.6 $\pm$ 1.8	27.8 $\pm$ 1.6 29.8 $\pm$ 2.3 +7%
 10.3 30	19.3 $\pm$ 1.6 19.2 $\pm$ 1.4	15.3 $\pm$ 0.5 15.8 $\pm$ 1.2	36.0 $\pm$ 1.8 +3% 33.2 $\pm$ 3.2	29.5 $\pm$ 2.4 31.8 $\pm$ 2.0 +8%
 10.3 10.3	20.8 $\pm$ 1.7 19.3 $\pm$ 1.6	17.8 $\pm$ 1.0 15.3 $\pm$ 0.5	★ 33.6 $\pm$ 1.6 -14% 36.0 $\pm$ 1.8	27.8 $\pm$ 1.6 29.5 $\pm$ 2.4 +6%
 30 30	20.5 $\pm$ 2.0 19.2 $\pm$ 1.4	15.1 $\pm$ 1.0 15.8 $\pm$ 1.2	34.6 $\pm$ 1.8 +5% 33.2 $\pm$ 3.2	29.8 $\pm$ 2.3 31.8 $\pm$ 2.0 +7%

With bronchial obstruction the alveolar minute ventilation at the two frequencies was 0.67 ± 0.06 l/min and 0.71 ± 0.08 l/min, respectively. As was found with an un-obstructed airway, V_A was reduced when the ventilatory frequency was increased from 10.3 to 30 cycles/minute, in this case by 66%. Before and after bronchial obstruction, V_A was unchanged at the two frequencies.

With an un-obstructed airway a linear relationship existed between V_{Dphys} and the V_{Texp} (coefficient of correlation 0.97, regression equation $V_{Dphys} = 0.42 \cdot V_{Texp} + 19.2$).

The part of the minute volume going to V_{Dphys} was 0.89 ± 0.06 l/min at $f = 10.3$ and 1.5 ± 0.1 l/min at $f = 30$ cycles/minute ($p < 0.01$). V_{Dphys} , for each exhalation, was significantly less at $f = 30$ (42%) than at $f = 10.3$ cycles/minute ($p < 0.01$, Table 3).

V_{Danat} was unchanged while V_{Dalv} was reduced by 53 % ($p < 0.05$) when the ventilatory frequency was changed from 10.3 to 30 cycles/minute (Table 4).

The V_{Dphys}/V_{Texp} ratio increased from 0.55 ± 0.02 to 0.65 ± 0.02 ($p < 0.001$) as the ventilatory frequency was raised from 10.3 to 30 cycles/minute (Table 5). The V_{Danat}/V_{Texp} ratio increased with 81 % ($p < 0.001$) while the ratio V_{Dc}/V_{Texp} and the V_{Dalv}/V_{Texp} both were unchanged (Table 5).

With bronchial obstruction V_{Dphys} was reduced by 41 % ($p < 0.05$, Table 3) as the ventilatory frequency was raised. No significant changes in V_{Dphys} were seen on obstruction of the regional bronchus.

The ratio V_{Dphys}/V_{Texp} increased from 0.56 ± 0.03 at $f = 10.3$ to 0.67 ± 0.02 at $f = 30$ cycles/minute ($p < 0.01$, Table 3).

At both ventilatory frequencies the V_{Dphys}/V_{Texp} ratios were unchanged when the ventilation of un-obstructed and obstructed airways was compared (Table 3).

With an un-obstructed airway no changes in gas distribution were seen when comparing $f = 10.3$ to $f = 30$ cycles/minute.

In the obstructed right caudal lobe the ventilation was reduced at both frequencies (n.s.). At $f = 10.3$ cycles/minute the ventilation in the un-obstructed left caudal lobe was reduced by 5 % while it increased by 7 % at $f = 30$ cycles/minute ($p < 0.05$, Table 6). The reduced ventilation in both the obstructed right caudal lobe and the un-obstructed left caudal lobe at $f = 10.3$ was compensated for by an increased ventilation, especially in the right cranial lobe. At $f = 30$ cycles/minute the reduction in the obstructed field was compensated for by an increased ventilation in the un-obstructed left caudal and cranial lobes. The difference between the ventilation in the right cranial lobe at the two frequencies was significant ($p < 0.05$).

Lung perfusion to the left cranial lobe after bronchial obstruction was significantly higher at $f = 10.3$ than at $f = 30$ cycles/minute ($p < 0.05$).

In the other pulmonary fields no great differences were seen (Table 7). With bronchial obstruction and $f = 10.3$ the perfusion in the obstructed right caudal lobe was increased by 7 % while a slight reduction (4 %) was seen in the same pulmonary field at $f = 30$ (n.s., Table 7).

DISCUSSION

The experimental model presented in this investigation was primarily designed to facilitate evaluation of artificial ventilation using high and low ventilatory frequencies with an un-obstructed and an obstructed regional bronchus. As a basis for the comparison, normoventilation was controlled by reference to the CO_2 fraction, i.e. unchanged CO_2 production at the two frequencies.

Several publications (COLLIER et al 1955, GEUBELLE 1958, BROWN & ELAM 1964) have shown reliable results of infra-red CO₂ analyses on end-tidal expired gas under physiological conditions. However, applied to pulmonary pathology, the method is doubtful as uncertainty exists as to whether the analysed end-tidal expired gas represents alveolar gas only or alveolar gas mixed with dead-space gas.

In spite of the uncertainty with infra-red CO₂ analyses as a ventilatory control method with bronchial obstruction, normoventilation was maintained by reference to blood gas analyses and quantitative analyses of expired gas (Table 2). The variations in PaCO₂ under the different conditions were less than $\pm 5\%$.

For evaluation of the results it was important that inspiration at the two frequencies could be closely reproduced with regard to course and duration. Accordingly an experimental model with the ventilatory frequencies 12 and 30 cycles/minute and inspiration times of 20 % and 50 %, respectively, was chosen, i.e. inspiration lasted for 1 s, irrespective of frequency. It was later found, however, that the duration of inspiration was not the same at both frequencies; control measurements via pressure registrations showed that the frequencies in fact were 10.3 and 30 cycles/minute. This deviation meant a duration of inspiration 0.16 s' longer and a smaller increase in tidal volume at the lower frequency. These differences resulted in only marginal effects which were shown to be negligible.

During artificial ventilation with high and low ventilatory frequencies the end-inspiratory tracheal pressure is of great interest as regards the risk of pulmonary damage as well as the effect on pulmonary capillary flow. With an un-obstructed airway the end-tidal tracheal pressure was maximally 1.7 kPa at $f = 10.3$ and was little over 50 % of these values at $f = 30$ cycles/minute. These pressure levels offered a good margin of safety.

After obstruction of the bronchus we registered 1.9 and 1.0 kPa, respectively. These pressure levels are also on a safe and low

level. OVENFORS (1964) showed that interstitial emphysema did not occur in healthy dogs until pressure levels of about 3 kPa were reached. The initial tracheal peak pressure varied between 1.6 and 3.5 kPa. This peak was of no great importance as it was instantaneous and never reached the alveoli.

The total in- and exsufflation time varied between 0.37 and 0.94 s (Table 1). In order to achieve larger tidal volumes at $f = 10.3$ and un-obstructed airways a longer time for gas transport was needed than at $f = 30$. This was also in agreement with earlier results (LINDAHL & OKMIAN 1977 a). The duration of exsufflation also followed the tidal volume. Bronchial obstruction, at both frequencies, required a longer duration of insufflation than un-obstructed airway. Paradoxically, the duration of exsufflation was longer before the bronchus was obstructed both at $f = 10.3$ and at $f = 30$ cycles/minute. The results from the radiospirometrical part of the investigation gave a reasonable explanation.

The un-obstructed pulmonary regions were overventilated, resulting in a higher end-inspiratory tracheal pressure with a greater pressure gradient and a corresponding reduction in the exsufflation times compared to the conditions before bronchial obstruction.

By adding in- and exsufflation times, the highest ventilatory frequency at the tidal volumes used and the maximum pulmonary ventilation under the actual mechanical conditions could be calculated. At $f = 10.3$ with an un-obstructed airway, the minute ventilation could be increased by 530 % and at $f = 30$ cycles/minute by 240 %. Corresponding values for the conditions after bronchial obstruction were 407 and 200 %, respectively. These results indicate that the "waste" of time due to dead-space ventilation is considerable and rises with higher ventilatory frequencies. The tidal volume at $f = 30$ cycles/minute was only little more than 50 % of the tidal volume at $f = 10.3$ cycles/minute. However, to accomplish in- and exsufflation at $f = 30$ cycles/minute, 70 - 75 % of the time at $f = 10.3$ cycles/minute was needed.

The $V_{D_{phys}}/V_{T_{exp}}$ ratio represents ventilation of the non- CO_2 producing parts of the ventilatory system. At $f = 30$ the ratio was, as expected, significantly higher than at $f = 10.3$ before and after bronchial obstruction. Similar results have also been published by HEDENSTIERNA (1972) in adults and by LUNN et al (1975) in dogs. A more detailed analysis of which part of the ventilatory system - tubing, airways or alveoli - that accounted for most of the "wasted" ventilation was achieved by dividing up the physiological dead-space into V_{D_C} , $V_{D_{anat}}$ and $V_{D_{alv}}$ and relating the different components to $V_{T_{exp}}$.

It was shown that the $V_{D_{anat}}/V_{T_{exp}}$ ratio was significantly increased ($p < 0.001$) when the ventilatory frequency was changed from 10.3 to 30 cycles/minute, while the ratio $V_{D_C}/V_{T_{exp}}$ and $V_{D_{alv}}/V_{T_{exp}}$ were unchanged. According to HEDENSTIERNA & MCCARTHY (1975) the higher V_D/V_T ratio at higher frequencies depended on a significant increase in the ratio between compressed gas volume and tidal volume. The same authors also noticed that the anatomical dead-space increased by 250 % as the end-tidal tracheal pressure rose from approximately 1 to 3 kPa. On the other hand our measurements showed a more reasonable increase (2 %) in the anatomical dead-space at the end-inspiratory tracheal pressure levels used. This difference might to some extent be due to the ventilator and method used by HEDENSTIERNA and MCCARTHY.

Before bronchial obstruction an even gas distribution and lung perfusion were shown to exist by the Xe^{133} radiospirometry, irrespective of the ventilatory frequency used. Obstructing the bronchus did to some extent reduce the ventilation within the obstructed field, an effect which was more pronounced at $f = 30$ than at $f = 10.3$ cycles/minute, while lung perfusion in the obstructed field increased at $f = 10.3$ and decreased at $f = 30$ cycles/minute. Air trapping at $f = 30$ with a short exsufflation time may explain these features (Fig. 4). A considerable decrease in ventilation and perfusion was seen in this experiment where the obstruction became important in relation to the bronchial diameter of the animal. The decrease in perfusion might be explained by either an increase in mean alveolar pressure or hypoxia due to hypoventilation (ARBORELIUS J:r. 1965).

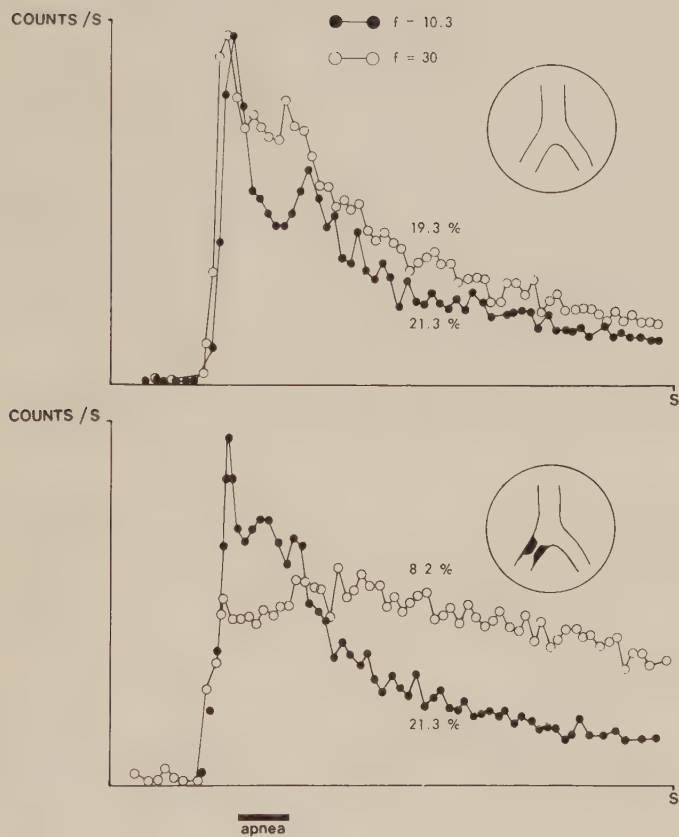


Fig. 4. Percentage lung perfusion (plateau phase) and wash-out curves (slope phase) in the right lower lobe at $f = 10.3$ and $f = 30$ before and after bronchial obstruction. The prolonged plateau phase, open circles lower curve, indicates air trapping.

This investigation showed that normoventilation at a low ventilatory frequency could be used during anaesthesia without deleterious mechanical conditions, for the ventilation of species whose breathing frequency under normal conditions, is high. Only when compliance is extremely low may a high ventilatory frequency and low tidal volume be advantageous. However, the present results indicate that this type of ventilation may imply risks when bronchial resistance is high. During these circumstances high respiratory frequency may cause hyperinflation of lung regions with long time constants and eventually cause lung rupture. A sufficient time must be left for areas with long time constants, to empty themselves during exhalation, which cannot be facilitated by any artificial means. This implies that a rapid insufflation as obtained with a decelerated flow and reasonable tidal volumes should give the best of possibilities for adequate ventilation of the critically diseased lung.

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EXPERIMENTAL STUDIES ON ARTIFICIAL
VENTILATION USING THE TVM-VENTILATOR
VI. The circulatory response to specific
ventilatory patterns

STEN LINDAHL, JAN KUGELBERG and LUDVIG OKMIAN

From the Departments of Paediatric Surgery, and Thoracic
Surgery, University Hospital, S-221 85 Lund, Sweden

Short running title: TVM-ventilator - Ventilatory patterns and
circulation

ABSTRACT

The circulatory response to different ventilatory patterns during artificial ventilation was examined in 17 sternotomized piglets.

The mechanics of ventilation, the pulmonary vascular resistance, the systemic vascular resistance, and the stroke work for both heart ventricles were determined by measurement of airway pressures, pleural pressure, circulatory pressures, and by electromagnetic measurement of blood flow.

A constant CO_2 tension level was maintained in all investigations by reference to analyses of the end-tidal infra-red CO_2 fraction and arterial CO_2 tension. The greatest variation in mean values for end-tidal CO_2 tension was 0.2 kPa.

Total compliance and lung compliance were lower at a ventilator volume/pressure quotient of 20 compared to those at 80 ml/kPa and at $f = 30$ compared to $f = 11$ cycles/minute.

Higher cardiac output, lower pulmonary vascular resistance and systemic vascular resistance were measured at $f = 11$ (inspiration 20 %) compared to $f = 30$ (inspiration 50 %).

An increase of inspiration time by about 100 % at the lower ventilatory frequency ($f = 11$) resulted in a moderately increased work load for the right heart, which was also reflected by a small decrease in cardiac output (7 %).

Changes in the duration of inspiration by about 100 % at the higher ventilatory frequency ($f = 30$) resulted in a significant but uncompensated decrease in cardiac output and stroke volume.

These results demonstrate the value of a rapid insufflation in order to give longer expiration time per minute for the benefit of the venous return and cardiac output.

The influence of endotracheal pressure on pulmonary circulation and cardiac output in adults during artificial ventilation has been under discussion for several decades and was initiated by the work of WERKÖ (1947) and CURNAND et al (1948). During this period many ventilators have been developed, representing a wide variety of tracheal pressure profiles tested under anaesthesia and in intensive care (OKMIAN 1966, BERGMAN 1967, MUSHIN et al 1969, BAKER 1971, NORDSTRÖM 1972, JOHANSSON & LÖFSTRÖM 1975).

On ventilation with the TVM-ventilator (Tidal Volume Monitoring, OKMIAN 1973) a decelerated gas flow is used during insufflation. This gas flow may be altered by a change of the ventilator's volume/pressure quotient (C_{vent}). An increase of the C_{vent} thus means a lower tracheal peak pressure combined with a longer insufflation time (LINDAHL & OKMIAN 1977 b).

In our previous work, gas distribution and pulmonary circulation were investigated at different C_{vent} settings (LINDAHL et al 1977a), and with regard to duration of inspiration (LINDAHL et al 1977 b) and ventilatory frequencies (LINDAHL et al 1977 c). Normoventilation was maintained throughout, and Xe^{133} radiospirrometry was used for the determinations (MIÖRNER 1968, ARBORELIUS et al 1970). Important reciprocal differences in lung perfusion at the tracheal pressures examined could not be detected. Radiospirrometry, however, exposes only the compensated haemodynamic net-effect, and detailed circulatory parameters were not achieved.

The present series of experiments was carried out in order to gain a more substantial knowledge of haemodynamics at different C_{vent} settings, inspiration times and ventilatory frequencies. The ultimate aim of our efforts was to find a method for efficient mechanical ventilation of children with a minimal disturbance of circulation.

MATERIAL

A total of 17 piglets of the Swedish native breed, with body weights between 6 and 12 kg, were used. The distribution of animals at different stages of the study is shown in Table 1.

SYMBOLS

b.w.	Body weight, (kg),
C_L	Lung compliance, (ml/kPa),
C_{THX}	Thoracic compliance, (ml/kPa),
C_{TOT}	Total compliance, (ml/kPa),
C_{vent}	Ventilator volume/pressure quotient, (ml/kPa),
f	Ventilatory frequency, (cycles/minute),
h.r.	Heart rate, (beats/minute),
P_aCO_2	Arterial carbon dioxide tension, (kPa),
P_aO_2	Arterial oxygen tension, (kPa),
P_{Ao}	Aortic pressure, (kPa),
P_{AP}	Pulmonary arterial pressure, (kPa),
PCW	Pulmonary capillary wedge pressure, (kPa),
P_{ei}	End-inspiratory tracheal pressure, (kPa),
$P_{ET}CO_2$	End-tidal carbon dioxide tension, (kPa),
P_{la}	Left atrial pressure, (kPa),
P_{peak}	Tracheal peak pressure, (kPa),
P_{pl}	Pleural pressure, (kPa),
P_{ra}	Right atrial pressure, (kPa),
PVR	Pulmonary vascular resistance, (units),
$\dot{Q}$	Cardiac output, (l/min),
SV	Stroke volume, (ml),
SVR	Systemic vascular resistance, (units),
SWL	Stroke work left ventricle, (Nm),
SWR	Stroke work right ventricle, (Nm),
t_{insuff}	Duration of insufflation, (s),
t_{pl}	Duration of rising pleural pressure, (s),
V_{Tvent}	Tidal volume, read on the ventilator's dial, (ml).

TABLE 1. The six examined ventilatory settings, tracheal profiles and mean values and standard deviation of the mean values for $P_{ET}CO_2$ at the different ventilatory settings.

MODEL	A		B		C		D		E		F	
n	6		6		6		14		6		6	
C_{vent} ml/kPa	20	80	20	20	80	80	40	40	40	40	40	40
f	20	20	20	20	20	20	11	30	11	11	30	30
%inspic	33	33	20	50	20	50	20	50	20	50	20	50
Inspic. time s.	1.0	1.0	0.6	1.5	0.6	1.5	1.1	1.1	1.1	2.7	0.4	1.0
Inspic. time per min. s.	20	20	12	30	12	30	12	30	12	30	12	30
$P_{ET}CO_2$, kPa	5.4±0.17		5.5±0.20		5.4±0.15		5.4±0.13		5.6±0.21		5.8±0.16	
							4.9±0.12		4.8±0.11		4.9±0.27	
									4.8±0.27		4.6±0.25	
											4.6±0.16	
TRACHEAL PROFILE												

METHODS

Stroke-work and cardiac output were determined for the two ventricles separately under normoventilation with 6 specific endotracheal pressure profiles. Pulmonary as well as systemic vascular resistance was also calculated. Mechanics of ventilation was estimated by means of total compliance, as well as compliance of the lungs and thoracic wall separately. Calculations were made from tidal volumes and pressures in the trachea and pleura.

Continuous, simultaneous recordings were made of the two atrial pressures and of the pressures in the aorta and pulmonary artery. Cardiac output was measured directly over the main stem of the pulmonary artery. The parameters were registered on two synchronized recorders (Fig. 1). Ventilatory settings and the endotracheal pressure profiles are given in Table 1.

Pressure measurements and calibrations

Electrodynamic pressure gauges (Siemens-Elema EMT 34), amplifiers, and ink-jet recorders (EM 41 and 81) were used. The tracheal pressures were measured from the tracheal tube connection. Instruments for tracheal and pleural pressure measurements were calibrated against a 30 cm high column of water and instruments of circulatory pressures were calibrated against a water column corresponding to 100 mm Hg.

Cardiac output

An electromagnetic flow meter (Nycotron 372) connected to the recorder (EM 81) was used. Its probe encircled the main stem of the pulmonary artery. The diameter of the probe was chosen so that it was somewhat smaller than the diameter of the vessel, without causing a pressure gradient.

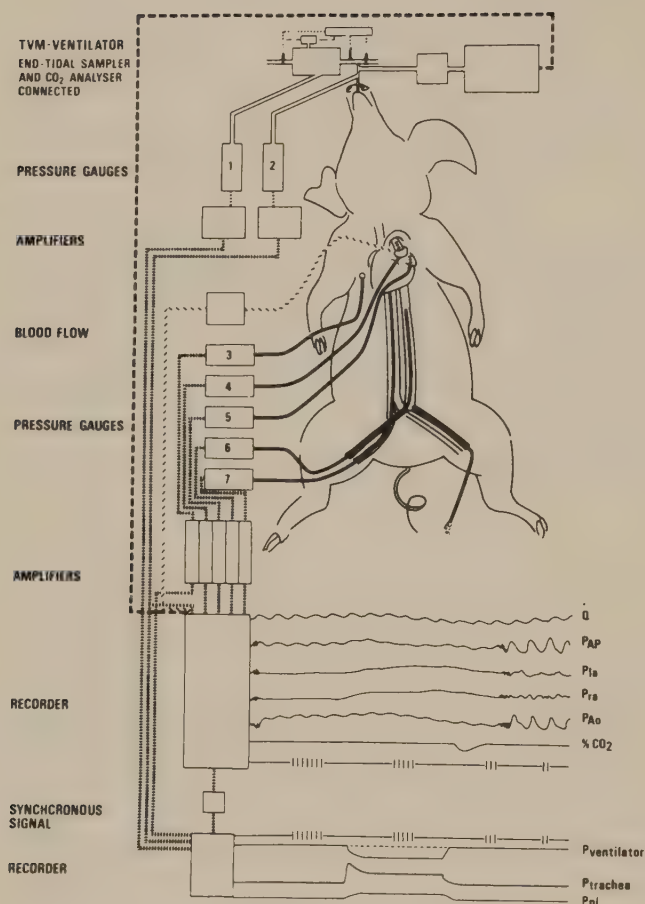


Fig. 1. Schematic presentation of the experimental set up and registrations.

In one experiment the cardiac output was determined by a thermodilution technique (Swan-Ganz, 7 F, Edwards Lab., USA). The test solution (isotonic saline, temperature $0 - +1^{\circ}\text{C}$) was injected rapidly into the right atrium. The tip of the catheter containing the thermistor was situated in the main stem of the pulmonary artery. The thermistor was connected to a digital computer (Model 9600, Cardiac Output Computer, Edwards Lab., USA). P_{AP} and PCW pressures were measured from the tip of the catheter. Right atrial pressure was measured from the connection available on this type of catheter.

Calculations

Total compliance:
$$C_{TOT} = \frac{V_{T_{vent}}}{P_{ei}}$$

Lung compliance
$$C_L = \frac{V_{T_{vent}}}{P_{ei} - P_{pl}}$$

Thoracic compliance
$$\frac{1}{C_{TOT}} = \frac{1}{C_L} + \frac{1}{C_{THX}}$$

Pulmonary vascular resistance
$$PVR = \frac{P_{AP} - P_{la}}{\dot{Q}}$$

Systemic vascular resistance
$$SVR = \frac{P_{Ao} - P_{ra}}{\dot{Q}}$$

Stroke work of the right ventricle
$$SWR = SV (P_{AP} - P_{ra})$$

Stroke work of the left ventricle
$$SWL = SV (P_{Ao} - P_{la})$$

Statistics

Current methods for mean values, standard deviations and standard error of the mean were used. Evaluation of the results was made with paired significance testing according to Student's t-test ($\star = p < 0.05$, $\star\star = p < 0.01$, $\star\star\star = p < 0.001$).

Anaesthesia

The animals were fasted for at least four hours before examination. Dridol (Droperidolum INN) 1 - 2 mg/kg b.w. and Ketalar (Ketaminum hydrochloride NFN) 30 - 50 mg/kg b.w. were injected intramuscularly. The animals were placed on an electrically heated operating table and intubated orotracheally with cuffed plastic tracheal tubes. Alloferin (Alcuronium NFN) 1 - 2 mg was injected intravenously when needed (muscle relaxation). Air was used as breathing gas. The body temperature was kept within 36.5 and 37.5°C. Each examination took 3 - 4 hours. During the examination 5.5 % glucose 3 - 4 ml/kg b.w./hour was given intravenously. After the examination the animals were sacrificed.

Normoventilation

Pulmonary ventilation was set at normoventilation, i.e. $P_{ET}CO_2$ 4.5 - 5.5 kPa, by reference to an end-tidal sampler and an infra-red CO_2 analyser (Godhart, Holland). Frequent momentary analyses of the end-tidal CO_2 fractions made it possible to avoid greater fluctuations in the CO_2 tension during each examination (Table 1). Arterial blood gases were analysed with conventional electrodes (Radiometer, Denmark) and correlated to body temperature. The infra-red CO_2 analyser was calibrated regularly during the examinations. Three test gases with known CO_2 concentrations within the range 2.5 - 6 % CO_2 were used. The mean values for P_aO_2 in all 20 investigations were, when air was used, 8.8 ± 0.16 kPa.

Procedure

The femoral artery was dissected free and catheterized for sampling and aortic pressure recordings. A catheter was placed in a femoral vein to allow infusions of 5.5 % glucose and injections of muscle relaxants. After sternotomy the pericardial sac was opened. The right and left auricles were catheterized for atrial

pressure recordings. A catheter was inserted through the infundibular wall of the ventricle into the main stem of the pulmonary artery. A balloon catheter was placed in the pleural space. The pericardial sac was left open and after careful haemostasis the thoracic cage was closed. The measurements then followed. With every new ventilatory setting all equipment was re-calibrated and the measurements were carried out after 10 - 15 minutes of unchanged pulmonary ventilation.

RESULTS

After injection of 2 mg Alloferin intravenously a reduction in both P_{AO} and Q was noticed after 30 and 90 seconds, respectively. The initial values were regained within 300 s. Our measurements were, in all instances, carried out more than 300 s' after the injection of the drug.

Mean values and standard error of the mean for $P_{ET}CO_2$ at the different ventilatory settings are shown in Table 1. The standard deviation from the mean values was within ± 0.13 to ± 0.27 kPa. Mechanical and circulatory data are presented in Tables 2 and 3.

C_{TOT} and C_L were both significantly lower at a C_{vent} of 20 than at a C_{vent} of 80 ($p < 0.05$), while C_{THX} was unchanged (Table 2). Neither at a C_{vent} of 20 nor 80 could any changes in compliance be detected, when the duration of inspiration was increased from 20 % to 50 % (Table 3). With constant durations of inspiration both C_{TOT} and C_L were significantly lowered ($p < 0.05$) when $f = 30$ cycles/minute was used compared to $f = 11$ (Table 2).

End-tidal pleural pressures did not change at different C_{vent} settings. The higher initial tracheal peak pressures at a C_{vent} of 20 did not, in any case, reproduce itself in the pleural space. On the other hand pleural pressures rose more rapidly to end-inspiratory pressure levels at a C_{vent} of 20 compared to the conditions with a C_{vent} of 80 ($p < 0.05$, Table 2). The end-inspira-

TABLE 2. Mechanics of ventilation at examined ventilatory settings.

Model	n	P _{peak} kPa	P _{el} kPa	P _{pl} kPa	V _{T,vent} ml/kg	t _{insuff} s.	t _{pl} s.	C _{TOT} ml/kPa/kg	C _L ml/kPa/kg	C _{THX} ml/kPa/kg
A	6	2.8 ⁺⁰ _{-0.22}	1.6 ⁺⁰ _{-0.17}	0.39 ⁺⁰ _{-0.05}	12.7 ⁺⁰ _{-0.52}	0.34 ⁺⁰ _{-0.03}	0.29 ⁺⁰ _{-0.01}	8.3 ⁺⁰ _{-0.9}	11.1 ⁺¹ _{-1.1}	38.4 ⁺⁹ _{-9.4}
		1.7 ⁺⁰ _{-0.38} ★ -39%	1.3 ⁺⁰ _{-0.14} ★ 20%	0.36 ⁺⁰ _{-0.04} -8%	12.7 ⁺⁰ _{-0.52} ±0%	0.48 ⁺⁰ _{-0.02} ★ +41%	0.60 ⁺⁰ _{-0.06} ★ +107%	10.3 ⁺⁰ _{-0.9} ★ +24%	14.6 ⁺¹ _{-1.5} ★ +32%	37.1 ⁺³ _{-3.7} -3%
B	6	2.8 ⁺⁰ _{-0.22}	1.6 ⁺⁰ _{-0.14}	0.38 ⁺⁰ _{-0.05}	12.7 ⁺⁰ _{-0.52}	0.34 ⁺⁰ _{-0.04}	0.29 ⁺⁰ _{-0.02}	7.9 ⁺⁰ _{-0.56}	10.6 ⁺⁰ _{-0.98}	35.4 ⁺⁴ _{-4.0}
		2.8 ⁺⁰ _{-0.20} ±0%	1.7 ⁺⁰ _{-0.18} +2%	0.39 ⁺⁰ _{-0.05} +3%	12.7 ⁺⁰ _{-0.52} ±0%	0.36 ⁺⁰ _{-0.07} +6%	0.30 ⁺⁰ _{-0.01} +3%	8.1 ⁺⁰ _{-0.89} +2%	10.9 ⁺¹ _{-1.5} +3%	34.5 ⁺⁴ _{-4.0} -3%
C	6	1.8 ⁺⁰ _{-0.26}	1.4 ⁺⁰ _{-0.14}	0.37 ⁺⁰ _{-0.04}	12.7 ⁺⁰ _{-0.52}	0.43 ⁺⁰ _{-0.03}	0.59 ⁺⁰ _{-0.06}	9.1 ⁺⁰ _{-0.77}	12.4 ⁺¹ _{-1.4}	36.5 ⁺³ _{-3.8}
		1.7 ⁺⁰ _{-0.25} -4%	1.3 ⁺⁰ _{-0.14} -7%	0.37 ⁺⁰ _{-0.04} ±0%	12.7 ⁺⁰ _{-0.52} ±0%	0.48 ⁺⁰ _{-0.03} +12%	0.62 ⁺⁰ _{-0.05} +5%	9.8 ⁺⁰ _{-0.83} +8%	13.8 ⁺¹ _{-1.9} +11%	38.2 ⁺⁴ _{-4.9} +5%
D	14	2.9 ⁺⁰ _{-0.16}	2.2 ⁺⁰ _{-0.09}	0.53 ⁺⁰ _{-0.05}	19.6 ⁺⁰ _{-0.35}	0.48 ⁺⁰ _{-0.03}	0.42 ⁺⁰ _{-0.04}	9.0 ⁺⁰ _{-0.4}	12.7 ⁺¹ _{-1.0}	36.4 ⁺³ _{-3.2}
		1.7 ⁺⁰ _{-0.14} ★ -40%	1.3 ⁺⁰ _{-0.08} ★ -41%	0.33 ⁺⁰ _{-0.04} ★ -44%	10.3 ⁺⁰ _{-0.32} ★ -47%	0.37 ⁺⁰ _{-0.02} ★ -23%	0.35 ⁺⁰ _{-0.03} -17%	8.3 ⁺⁰ _{-0.4} ★ -8%	10.8 ⁺⁰ _{-0.7} ★ -15%	36.0 ⁺⁴ _{-4.5} -1%
E	6	3.8 ⁺⁰ _{-0.29}	3.2 ⁺⁰ _{-0.24}	0.84 ⁺⁰ _{-0.09}	19.9 ⁺⁰ _{-0.45}	0.45 ⁺⁰ _{-0.04}	0.45 ⁺⁰ _{-0.06}	6.3 ⁺⁰ _{-0.39}	8.5 ⁺⁰ _{-0.53}	24.9 ⁺² _{-2.7}
		3.8 ⁺⁰ _{-0.29} ±0%	3.2 ⁺⁰ _{-0.24} ±0%	0.84 ⁺⁰ _{-0.09} ±0%	19.9 ⁺⁰ _{-0.45} ±0%	0.45 ⁺⁰ _{-0.04} ±0%	0.45 ⁺⁰ _{-0.06} ±0%	6.3 ⁺⁰ _{-0.39} ±0%	8.5 ⁺⁰ _{-0.53} ±0%	24.9 ⁺² _{-2.7} ±0%
F	6	2.1 ⁺⁰ _{-0.28}	1.7 ⁺⁰ _{-0.13}	0.40 ⁺⁰ _{-0.06}	10.0 ⁺⁰ _{-0.45}	0.38 ⁺⁰ _{-0.04}	0.38 ⁺⁰ _{-0.06}	6.1 ⁺⁰ _{-0.42}	8.2 ⁺⁰ _{-0.73}	28.1 ⁺⁴ _{-4.5}
		2.1 ⁺⁰ _{-0.28} ±0%	1.7 ⁺⁰ _{-0.13} ±0%	0.40 ⁺⁰ _{-0.06} ±0%	10.0 ⁺⁰ _{-0.45} ±0%	0.38 ⁺⁰ _{-0.04} ±0%	0.38 ⁺⁰ _{-0.06} ±0%	6.1 ⁺⁰ _{-0.42} ±0%	8.2 ⁺⁰ _{-0.73} ±0%	28.1 ⁺⁴ _{-4.5} ±0%

TABLE 3. Circulatory data of the examined ventilatory settings.

Model/ n	$\dot{Q}$ l/min	P_{AP} kPa	P_{Ia} kPa	PVR units	P_{Ao} kPa	P_{ra} kPa	SVR units	SV ml	h.r.	SWR Nm	SWL Nm
A/6	1.13 ± 0.23	3.2 ± 0.35	1.3 ± 0.25	2.4 ± 0.50	13.8 ± 1.48	0.10 ± 0.11	14.1 ± 2.43	6.7 ± 1.4	172 ± 12	0.16 ± 0.03	0.63 ± 0.15
	1.15 ± 0.22	2.9 ± 0.18	1.2 ± 0.27	1.9 ± 0.50	14.4 ± 1.56	0.10 ± 0.18	14.1 ± 2.16	6.6 ± 1.3	177 ± 14	0.13 ± 0.02	0.64 ± 0.13
	+ 2 %	- 10 %	- 9 %	- 21 %	+ 4 %	-	± 0 %	- 1 %	+ 3 %	- 19 %	+ 2 %
B/6	1.19 ± 0.24	3.5 ± 0.54	1.2 ± 0.13	2.1 ± 0.52	14.6 ± 1.75	0 ± 0.17	14.0 ± 2.16	6.9 ± 1.4	175 ± 12	0.18 ± 0.04	0.70 ± 0.17
	1.11 ± 0.25	3.7 ± 0.22	1.5 ± 0.25	2.6 ± 0.55	13.8 ± 1.77	0.10 ± 0.16	14.3 ± 2.20	6.4 ± 1.5	178 ± 13	0.17 ± 0.03	0.60 ± 0.16
	$\star - 7$ %	+ 6 %	+ 22 %	+ 25 %	$\star - 5$ %	-	+ 2 %	$\star - 7$ %	+ 2 %	- 6 %	$\star - 14$ %
C/6	1.19 ± 0.22	3.2 ± 0.33	1.4 ± 0.23	1.8 ± 0.47	15.5 ± 1.77	0.11 ± 0.18	14.7 ± 2.33	6.7 ± 1.3	178 ± 15	0.15 ± 0.02	0.70 ± 0.14
	1.10 ± 0.20	2.9 ± 0.30	1.4 ± 0.23	1.8 ± 0.55	14.9 ± 2.02	0.10 ± 0.21	15.1 ± 2.29	6.0 ± 1.2	185 ± 17	0.12 ± 0.02	0.60 ± 0.12
	- 8 %	- 9 %	± 0 %	± 0 %	- 4 %	-	+ 3 %	$\star - 10$ %	+ 4 %	- 20 %	- 14 %
D/14	1.27 ± 0.12	3.3 ± 0.23	1.4 ± 0.30	1.8 ± 0.35	13.5 ± 1.0	0.49 ± 0.17	11.3 ± 1.1	7.4 ± 0.78	172 ± 7.6	0.16 ± 0.02	0.67 ± 0.08
	1.13 ± 0.10	2.9 ± 0.36	0.88 ± 0.20	2.0 ± 0.41	13.0 ± 0.76	0.10 ± 0.07	12.6 ± 1.2	6.9 ± 0.75	171 ± 8.2	0.14 ± 0.02	0.61 ± 0.06
	$\star - 11$ %	- 12 %	- 37 %	+ 12 %	- 4 %	$\star - 85$ %	+ 12 %	- 7 %	± 0 %	- 12 %	- 9 %
E/6	1.07 ± 0.16	2.8 ± 0.19	1.2 ± 0.26	1.6 ± 0.43	12.9 ± 1.24	0.47 ± 0.11	12.5 ± 1.89	6.7 ± 0.96	160 ± 2.6	0.11 ± 0.02	0.60 ± 0.10
	0.99 ± 0.17	5.7 ± 0.26	1.2 ± 0.54	5.1 ± 0.75	13.7 ± 1.31	0.60 ± 0.16	14.7 ± 2.27	5.6 ± 0.93	178 ± 8.7	0.22 ± 0.04	0.54 ± 0.10
	- 7 %	$\star - 107$ %	± 0 %	$\star - 223$ %	+ 6 %	+ 28 %	$\star + 18$ %	- 16 %	+ 11 %	+ 100 %	- 10 %
F/6	1.05 ± 0.14	2.4 ± 0.19	0.93 ± 0.37	1.7 ± 0.71	12.9 ± 1.18	0.11 ± 0.14	13.1 ± 1.93	6.9 ± 0.92	153 ± 6.2	0.12 ± 0.02	0.63 ± 0.10
	0.97 ± 0.15	2.4 ± 0.18	0.89 ± 0.33	1.9 ± 0.61	12.4 ± 1.16	0.11 ± 0.05	14.0 ± 2.2	6.1 ± 0.90	160 ± 4.5	0.10 ± 0.01	0.53 ± 0.09
	$\star - 8$ %	± 0 %	- 4 %	+ 12 %	- 4 %	± 0 %	+ 7 %	$\star - 12$ %	+ 5 %	- 17 %	$\star - 16$ %

tory pleural pressure was significantly higher at $f = 11$ compared to $f = 30$ ($p < 0.001$, Table 2).

Cardiac output, stroke volume and aortic pressure were significantly reduced ($p < 0.05$) as the duration of inspiration at a C_{vent} of 20 was increased from 20 % to 50 % of the breathing cycle. Corresponding changes with a C_{vent} of 80 did not result in any significant change of $\dot{Q}$ or aortic pressure. The stroke volume on the other hand was slightly reduced ($p < 0.05$, Table 3).

Using the same duration of inspiration (approximately 1 s) a significantly lower cardiac output was registered at $f = 30$ in comparison to $f = 11$ ($p < 0.05$).

Increasing the duration of inspiration at $f = 11$ from 20 % to 50 % (i.e. from 1.1 s to 2.7 s) only resulted in a reduction of cardiac output by 7 % (n.s.), while increasing the duration of inspiration from 20 % to 50 % at $f = 30$ cycles/minute (i.e. from 0.4 s to 1.0 s), resulted in a significant reduction of cardiac output ($p < 0.001$) as well as of stroke volume ($p < 0.01$, Table 3).

Neither at a C_{vent} of 20 or 80, nor at $f = 30$ cycles/minute could important changes of P_{AP} and P_{la} be noticed when the duration of inspiration was changed from 20 % to 50 %. Accordingly this means only that small variations were produced in the pulmonary vascular resistance (Table 3).

At $f = 11$ cycles/minute a large increase in P_{AP} (107 %, $p < 0.001$) was seen when duration of inspiration was prolonged from 20 to 50 %, while P_{la} was unchanged (Fig. 2, Table 3). The pulmonary vascular resistance at the same time increased by 223 % ($p < 0.001$, Fig. 2, Table 3). These changes in the pulmonary circulation were compensated for by an increase in the stroke work of the right ventricle by 100 % ($p < 0.05$) and by an increase in heart rate of 11 %. These changes resulted in a reduction of the cardiac output by only 7 % (Fig. 2, Table 3).

Only marginal changes in the systemic circulation were measured with the different tracheal pressure profiles. With $f = 11$ cycles/

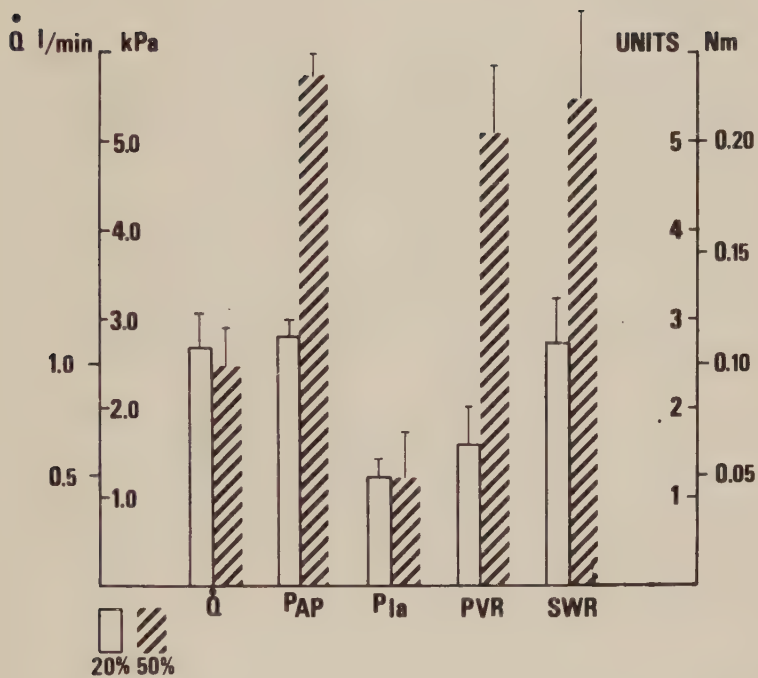


Fig. 2. Some circulatory changes at $f = 11$ when duration of inspiration was increased from 20 (white staples) to 50 % (filled staples).

minute and an increase in the duration of inspiration from 20 % to 50 %, an increase of the systemic vascular resistance by 18 % ($p < 0.05$) was measured. With $f = 30$ cycles/minute a reduction of left ventricular stroke work by 16 % ($p < 0.01$) was recorded with longer inspiration times (Fig. 3, Table 3).

DISCUSSION

Electromagnetic flow measurements, used in 19 of our 20 experiments, imply a heavy surgical procedure, which will traumatize the animal. Furthermore, the pulmonary tissue could be affected during certain surgical manoeuvres. The electromagnetic method was chosen chiefly for two reasons. Firstly the team at the laboratory has had many years of experience with the method (KUGELBERG 1971). Secondly the invasive surgical method offers better possibilities for measurements of the left atrial pressure.

An important error in electromagnetic flow measurements appears if the position of the probe is changed in relation to the direction of the blood stream. In order to fix the position of the probe satisfactorily, its diameter was chosen so that it was somewhat smaller than the diameter of the vessel.

With indicator flow measurement, which was used for comparison in one case, no invasive surgical intervention was needed. The indicator could either be a radioactive substance, a dye or a fluid of a known temperature. Recirculation of the indicator is considered to be the most common, and important, source of error. Using thermodilution, this source of error is very small. Instead, methodological difficulties are involved in the exact calibration of test solution temperatures and the thermistor. Values, registered with thermodilution, did not significantly deviate from those measured by electromagnetic flow meter.

Artificial ventilation, using the same duration of inspiration, ventilatory frequency, and tidal volume, showed a reduction in total

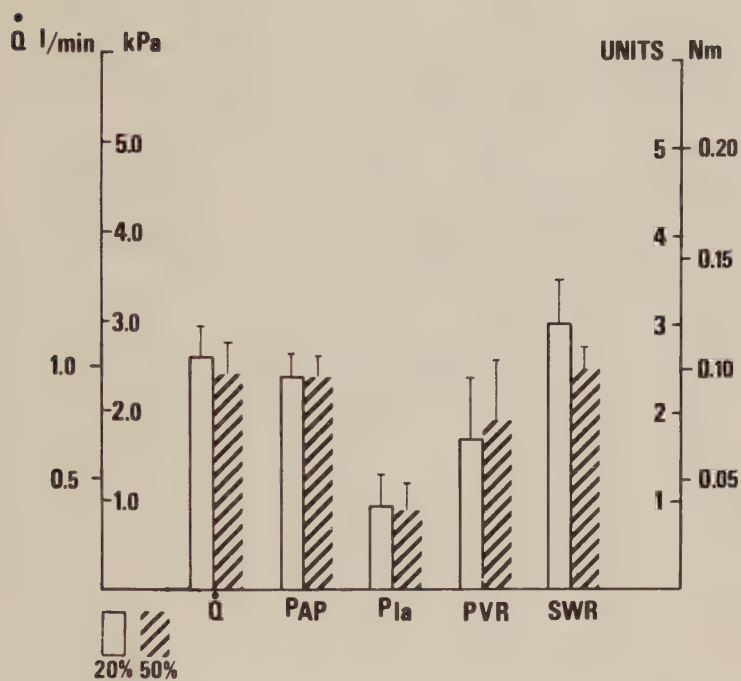


Fig. 3. Some circulatory changes at $f = 30$ cycles/minute when duration of inspiration was increased from 20 % (white staples) to 50 % (filled staples).

compliance with a C_{vent} of 20 compared to that with a C_{vent} of 80. This reduction could be localized to the lung compliance. LINDAHL et al (1977 a) reported that a low C_{vent} resulted in a slightly more uneven gas distribution after bronchial obstruction. The authors claimed that the most important reason for this was the more rapid filling of the easily ventilated pulmonary regions at a C_{vent} of 20. In this series the pleural spaces have been mechanically affected during the surgical performance, which in agreement with previous results could explain the difference in lung compliance between the two C_{vent} settings. Contrary to what LINDAHL et al (1977 c) have noticed in healthy lungs (no thoracotomy), a reduction in total compliance and lung compliance was determined at $f = 30$ compared to $f = 11$ cycles/minute. A possible explanation could be that small tidal volumes and low endotracheal pressures at $f = 30$ were unable to ventilate the affected lung regions as well as large tidal volumes and higher endotracheal pressures at the lower ventilatory frequency.

In spite of higher tracheal and pleural pressures at the lower ventilatory frequency, cardiac output was greater than at a high ventilatory frequency. Similar results have previously been reported by LUNN et al (1975). When the duration of inspiration was changed from 20 to 50 % at a C_{vent} of 20 cardiac output was significantly reduced.

However, a corresponding increase in inspiration time at a C_{vent} of 80 did not result in any statistically significant reduction in cardiac output. At $f = 30$ cycles/minute and on changing the inspiratory time from 20 to 50 % a significant reduction in cardiac output was shown at 50 %, pulmonary vascular resistance and right ventricular stroke work being unchanged. If, on the other hand, the duration of inspiration at $f = 11$ was increased from 20 to 50 %, (inspiration time/cycle increased from 1.1 to 2.7 s) pulmonary arterial pressure increased by 107 % and pulmonary vascular resistance by 223 % (Table 3). However, the filling pressure in the left atrium was unchanged due to a 100 % increase in right ventricular stroke work which was also reflected in the small reduction in cardiac output (Fig. 2).

Evidently, high tracheal and pleural pressures could be tolerated by the pulmonary circulation by an increase in the work done by the right ventricle. Prerequisite conditions for this were short periods of positive pressure, demanding rapid insufflations. This would increase the possibilities of prolonging expiration times per minute and would be advantageous for venous return, pulmonary circulation and cardiac work.

Similar observations have previously been published by several authors (COURNAND et al 1948, MORGAN et al 1966, CONWAY 1975, LUNN et al 1975, among others) and expressed as a reduced intra-thoracic mean pressure. However, intra-thoracic mean pressures are difficult to evaluate as they are correlated to the duration of inspiration as well as to the actual pressure levels. A high pressure for a short time during inspiration is preferable to a low pressure for a long time from circulatory point of view even if the mean intra-thoracic pressure is the same. Thus we regard prolonged expiration as the most important factor.

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ARTIFICIAL VENTILATION IN CHILDREN DURING
ANAESTHESIA USING THE TVM-VENTILATOR
Standards for ventilation, and ventilatory
patterns at frequencies of 15 and 20

STEN LINDAHL, LUDVIG OKMIAN and DICK THOMSON

From the Departments of Paediatric Surgery and Anaesthesia,
University Hospital, S-221 85 Lund, Sweden

Short running title: TVM-ventilator - Mechanics of ventilation
in children

ABSTRACT

Standards for artificial pulmonary ventilation at ventilatory frequencies of 15 and 20 cycles/minute, corresponding to a slight hyperventilation ($P_{ET}CO_2 = 4 \pm 0.5$ kPa), were defined in 16 children with healthy lungs and body weights between 2.6 and 22.6 kg. The TVM-ventilator with balanced anaesthesia was used during abdominal surgery. The duration of anaesthesia was 207 ± 96 minutes.

Adequate ventilator setting was achieved by close control of the alveolar CO_2 fraction and blood gas analysis. Tidal volumes and end-inspiratory tracheal pressures were read on the ventilator's dials. Pressures from the ventilator's pressure chamber and from the tracheal connections were recorded by electromanometers.

At $f = 20$ cycles/minute an approximately direct proportionality existed between tidal volume and body weight. The equation of regression was $V_{Tpat} = 12.3 \cdot \text{kg b.w.} - 2.1$. Coefficient of correlation was 0.99. The mean value V_{Tpat} per kg b.w. was 12.1 ± 1.4 ml/kg.

At $f = 15$ cycles/minute a linear relationship between tidal volume and kg b.w. was recorded. Regression equation was $V_{Tpat} = 14.6 \cdot \text{kg b.w.} + 16$. Coefficient of correlation was 0.97 and the mean value V_{Tpat} per kg b.w. was 15.9 ± 1.5 ml/kg. The regression equation at $f = 15$ revealed no direct proportionality.

A significant decrease in total compliance was recorded during the initial part of the surgical procedure. A rectilinear relationship existed between total compliance and kg b.w. The regression equation was $C_{TOT} = 11.2 \cdot \text{kg b.w.} - 12.5$, coefficient of correlation was 0.95. The mean value C_{TOT} per kg b.w. was 9.7 ± 0.54 ml/kPa/kg at $f = 20$.

The endotracheal peak pressure maintained a fairly constant pressure level independent of the initial pressure within the ventilator, the tidal volume and the body weight. This unexpected phe-

nomenon could be explained by the hypothesis that the proportional increase in total lung volume and functional residual capacity in the older children compensated for the higher pressures within the ventilator pressure chamber, when large tidal volumes were administered.

Standards for artificial ventilation of children have previously been published by RADFORD (1955), ENGSTRÖM et al (1962) and OKMIAN (1963), among others. RADFORD found a margin of error of 7 % using his nomogram for calculation of the ventilation in paralysed adults, corrections for temperature and metabolism being made. He also assumed the error in his nomogram to be even higher for paediatric patients, since few primary data were used.

To obtain an adequate alveolar ventilation, especially in children, factors such as respiratory rate, duration of inspiration, volume of dead-space and velocity of flow need consideration (for references, see MATTILA 1974). A knowledge of the volume of compressed gas in ventilator and the tubing systems is also essential (OKMIAN 1963, HADDAD & RICHARDS 1967). However, in a clinical investigation of paediatric patients, OKMIAN et al (1966 b) found a close correlation between pulmonary ventilation as calculated from RADFORD's nomogram, and that found to be required in practice, corrected for gas compression using pneumotachography with simultaneous control of capillary blood gases.

The TVM-ventilator (Tidal Volume Monitoring), incorporates close control of the actual ventilation by instantaneous recording of the delivered tidal volume on a dial instrument (OKMIAN 1963, OKMIAN 1973, OKMIAN et al 1974, LINDAHL & OKMIAN 1977a, b, LINDAHL et al 1977 a). Accordingly, when total compliance is altered, the corresponding volume change can be read off and corrected for. The aim of the present study was to obtain standards for artificial ventilation in children during anaesthesia and surgery, at two ventilatory frequencies.

MATERIAL

The series consisted of 16 children with normal lungs and body weights between 2.6 and 22.6 kg. The duration of anaesthesia was 207 ± 96 minutes. All operations were abdominal. Relevant data such as age, sex, weight, height, diagnosis, procedure and duration of anaesthesia, are listed in Table 1.

SYMBOLS

b.w.	Body weight, (kg),
C_{TOT}	Total compliance, (ml/kPa),
C_{vent}	Ventilator volume/pressure quotient, (ml/kPa),
f	Ventilatory frequency, (cycles/minute),
FiO_2	Fraction of oxygen in inspired gas,
ΔP	Instantaneous pressure change, (kPa),
P_aCO_2	Arterial carbon dioxide tension, (kPa),
P_aO_2	Arterial oxygen tension, (kPa),
PC	Ventilator pressure chamber,
P_{ei}	End-inspiratory tracheal pressure, (kPa),
$P_{ET}CO_2$	End-tidal carbon dioxide tension, (kPa),
P_{peak}	Tracheal peak pressure, (kPa),
P_{vent}	Pressure in the ventilator pressure chamber, (kPa),
Δt	Insufflation/unit time, (0.1 s),
t_{insuff}	Duration of insufflation, (s),
ΔV	Instantaneous gas amount change, (ml),
V_{TC}	Compressed gas in tubing, (ml),
V_{Tpat}	Calculated tidal volume, (ml),
V_{Tvent}	Tidal volume, read on the ventilator's dial, (ml),
	$(V_{Tvent} = V_{TC} + V_{Tpat})$.

TABLE 1.

Pat. No.	Age, years/ months	Sex	b. w. kg	Height cm	Diagnosis	Surgical procedure	Duration of anaesth. minutes
1	5/6	F	19.7	116	Reflux uret. dx.	Polithano-Leadbetter	135
2	0/9	F	5.1	63	Stenosis uret. dx	Davle's procedure	155
3	4/11	F	20.0	114	Reflux uret. dx	Polithano-Leadbetter	105
4	1/4	F	11.5	87	Pelvis ren. et uret. dupl. dx Reflux uret. dx	Polithano-Leadbetter	165
5	5/0	F	16.5	108	Pelvis ren. et uret. dupl. dx Reflux uret. sin	Polithano-Leadbetter	135
6	0/2	M	5.1	61	Aganglionosis coli	DuHamel procedure	300
7	6/2	M	16.6	110	Status post-oesophagitis erosiva	Coloninterpos. ad mod. Sherman	480
8	1/2	M	9.5	76	Atresia ani sup.	Stephen's procedure	250
9	8/0	F	22.6	128	Duct. pancreat. aberr.	Exploration	275
10	0/6	M	7.1	83	Stat. post. valv. uretrae. Stenosis uret. bilat.	Polithano-Leadbetter bilat.	280
11	0/1	F	4.2	50	Teratoma coli	Extirpation	210
12	3/11	F	17.5	105	Reflux uret. bilat.	Polithano-Leadbetter bilat.	135
13	4 days	F	2.6	46	Duodenal atresia	Duodeno-jejunostomy	130
14	5/4	F	17.0	108	Congen. choledochal cyst.	Roux-en-Y procedure	240
15	3/0	M	14.5	94	Reflux uret. sin.	Polithano-Leadbetter	155
16	1/8	F	10.5	82	Reflux uret. dx	Polithano-Leadbetter	160

METHODS

Anaesthesia

Anaesthesia was induced by inhalation of Fluothane (Halothane, NFN) in combination with oxygen and nitrous oxide. Celocurin (Suxamethonium, NFN) was used for intubation. After the patient had been intubated, balanced anaesthesia (Pethidinum, INN, N_2O/O_2) with Pavulon (Pancuronum, INN) for muscle relaxation was used.

Ventilator setting

Tidal volume, frequency and inspiration times were set on the TVM-ventilator. As the walls of the ventilator's pressure chamber are non-elastic the volume of gas delivered can be estimated automatically, according to the 2-pressure method (OKMIAN 1963) using a differential manometer. Any leakage in the ventilator-patient system could be detected from the dials. At the end of an inspiration the compressed gas within the ventilator is withheld in the pressure chamber. The amount of compressed gas in the tubing is calculated. This volume, for tubing 1 cm in diameter, was 10 ml/kPa. In all but two cases the inspired gas was humidified by an ultrasonic nebulizer. The humidifier increased the amount of compressed gas in the tubing to 20 ml/kPa.

Ventilatory frequencies of 15 and 20 cycles/minute and inspiration times of 20 and 33 % per cycle, respectively, were used. Thus the inspiration times set were 0.8 and 1.0 s, respectively.

The tidal volume ($V_{T_{vent}} - V_{T_C}$) was adjusted by reference to the CO_2 concentration of end-tidal gas (end-tidal sampler synchronized with the ventilator) measured with an infra-red CO_2 meter (Godhart, Holland). End-tidal CO_2 concentration was assumed to be the same as the mean alveolar. Samples for arterial blood gas analyses were withdrawn frequently from an indwelling arterial catheter (TODRES et al 1975) and analysed by conventional techniques. The correlation between $P_{ET}CO_2$ and P_aCO_2 was high ($r = 0.80$, regression equation $P_{ET}CO_2 = 0.81 \cdot P_aCO_2 + 0.83$).

Instantaneous pressure and volume measurements

Schematic representation of the set up appears in Fig. 1. The pressure changes in the trachea and in the ventilator's pressure chamber were measured with pressure gauges (Siemens-Elema EMT 34) and recorded on a direct ink-jet recorder (Siemens-Elema EM 41). The pressure gauges were calibrated by means of a mercury manometer.

The insufflation time (t_{insuff}) was estimated from the tracheal pressure recordings at the two ventilatory frequencies. Using reverse plethysmography (PC = plethysmograph, Fig. 1), instantaneous volume changes during insufflation (ΔV) and corresponding tracheal pressure changes (ΔP) were measured. The ratio between ΔV and ΔP describes the dynamic course of insufflation (LINDAHL & OKMIAN 1977b). Total compliance was calculated from volume and pressure measurements during static conditions at the end of the insufflation.

Statistics

Mean values with standard deviation of the mean and standard error of the mean were calculated using conventional methods. Evaluation of the results was made using paired significance testing according to Student's t-test.

Procedure

After induction of anaesthesia, intubation and insertion of the arterial catheter the patients were connected to the ventilator. The tidal volume was adjusted to give a moderate hyperventilation ($P_{\text{ET}}\text{CO}_2$ 4 ± 0.5 kPa) by reference to the CO_2 meter.

Due to technical errors arterial blood samples could only be collected in 13 of the 16 cases.

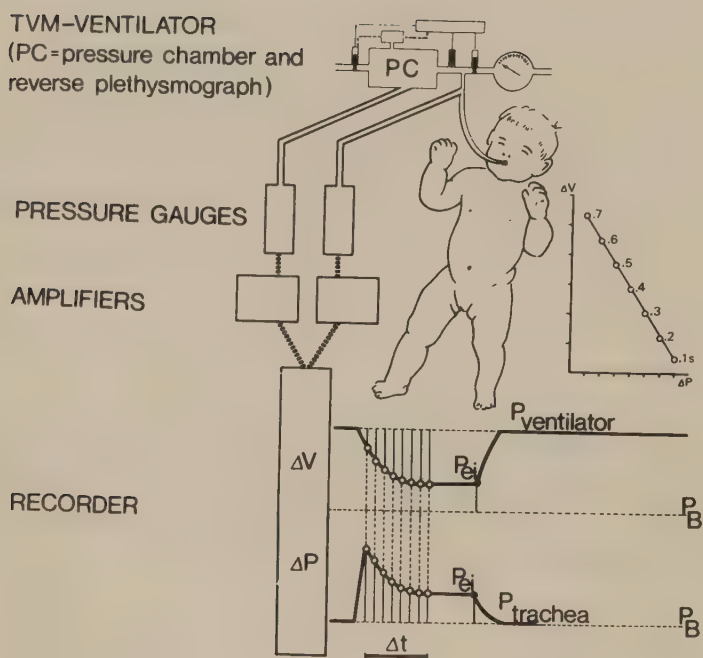


Fig. 1. Schematic presentation of the method. The pressure drop of curve $P_{ventilator}$ signifies the amount of gas that passes over from the ventilator to the airways (ΔV). The diagram $\Delta V / \Delta P$ is plotted from the corresponding points of the pressure recordings.

In all children ventilation was started using the respiratory rate of 20 cycles/minute and the fractional inspiration of 33 % of the entire breathing cycle. This setting was used during the initial surgical procedure. In 14 of the 16 cases the ventilatory frequency was then reduced to 15 cycles/minute and duration of inspiration to 20 %. The tidal volume was consequently adjusted to give an equal alveolar ventilation. At the end of the operation the arterial catheter was withdrawn and the patient extubated. In no case was there any need for postoperative ventilatory support.

RESULTS

Volume of pulmonary ventilation

At a ventilator frequency of 15 cycles/minute a slight hyperventilation with $P_a\text{CO}_2$ within the range of 3.9 ± 0.11 kPa was achieved by tidal volumes of 15.9 ± 1.5 ml/kg b.w. $P_a\text{O}_2$ was simultaneously recorded at 27 ± 1.0 kPa (FiO_2 0.33). A linear relationship existed between $V_{T_{\text{pat}}}$ and kg b.w. The regression equation was $V_{T_{\text{pat}}} = 14.6 \cdot \text{kg b.w.} + 16$ and the coefficient of correlation 0.97 (Fig. 2).

At $f = 20$ cycles/minute hyperventilation with $P_a\text{CO}_2$ within the range of 3.7 ± 0.14 was achieved by tidal volumes of 12.1 ± 1.4 ml/kg b.w. $P_a\text{O}_2$ was simultaneously recorded at 25 ± 1.2 kPa (FiO_2 0.33). A linear relationship existed between $V_{T_{\text{pat}}}$ and kg b.w. The regression equation was $V_{T_{\text{pat}}} = 12.3 \cdot \text{kg b.w.} - 2.1$ and the coefficient of correlation 0.99 (Fig. 2).

Ventilator and tracheal pressures

Recorded data are listed in Table 2.

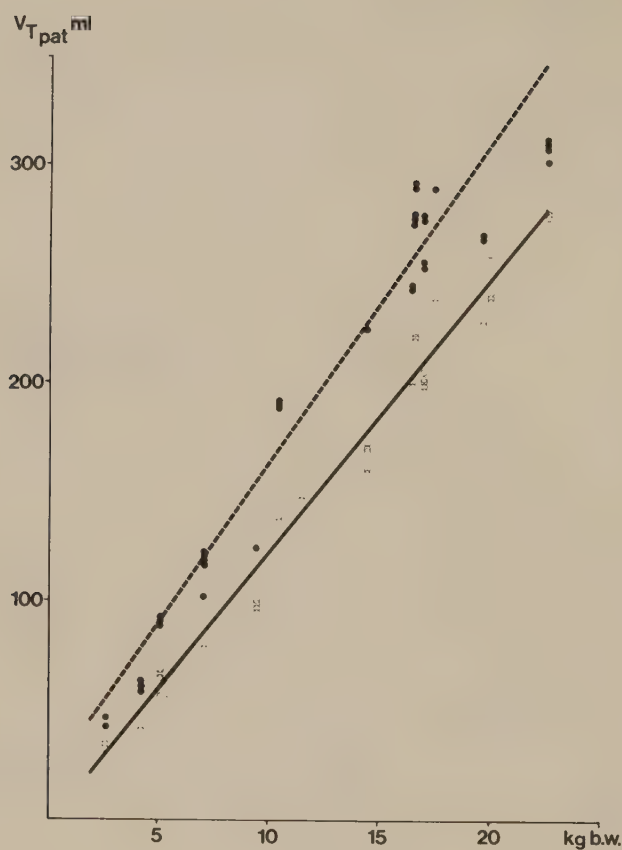


Fig. 2. Tidal volume and kg b.w. at $f = 15$ (filled circles) and at $f = 20$ (open circles). The regression equations and coefficients of correlation were respectively $V_{Tpat} = 14.6 \cdot \text{kg b.w.} + 16$, $r = 0.97$ (broken line) and $V_{Tpat} = 12.3 \cdot \text{kg b.w.} - 2.1$, $r = 0.99$ (continuous line).

TABLE 2. Mechanics of ventilation.

f	n	P _{vent} kPa	P _{peak} kPa	P _{ei} kPa	V _{T_c} ml	V _{T_{pat}} ml/kg b.w.	t _{insuff} s.	C _{TOT} ml/kPa/kg b.w.
15	14	4.3 ± 0.25	2.5 ± 0.11	1.6 ± 0.07	31 ± 1.9	15.9 ± 0.5	0.64 ± 0.02	10.1 ± 0.43
20	16	3.4 ± 0.22	2.0 ± 0.08	1.3 ± 0.06	25 ± 1.4	12.2 ± 0.3	0.58 ± 0.02	9.73 ± 0.54
Sign. n = 14		p < 0.001 ★★★	p < 0.001 ★★★	p < 0.001 ★★★	p < 0.001 ★★★	p < 0.001 ★★★	p < 0.01 ★★	n.s.

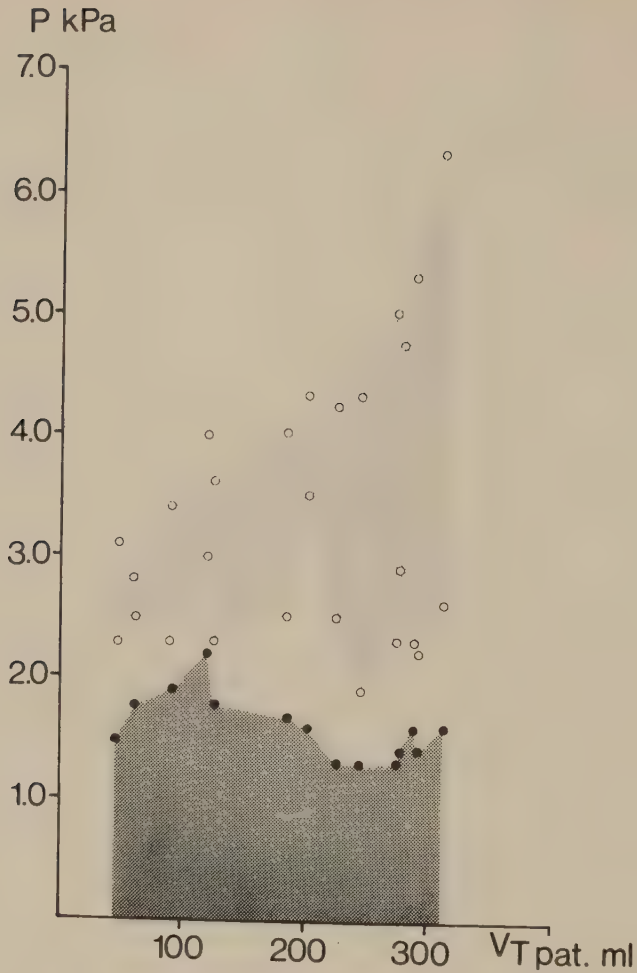


Fig. 3, a. Pressures in the ventilator pressure chamber (open circles, upper margin lightly shaded area), initial tracheal peak pressures (open circles, lower margin lightly shaded area) and end-inspiratory tracheal pressures (filled circles, upper margin heavily shaded area) at $f = 15$ cycles/minute. The tracheal pressure gradient during insufflation is shown by the white area.

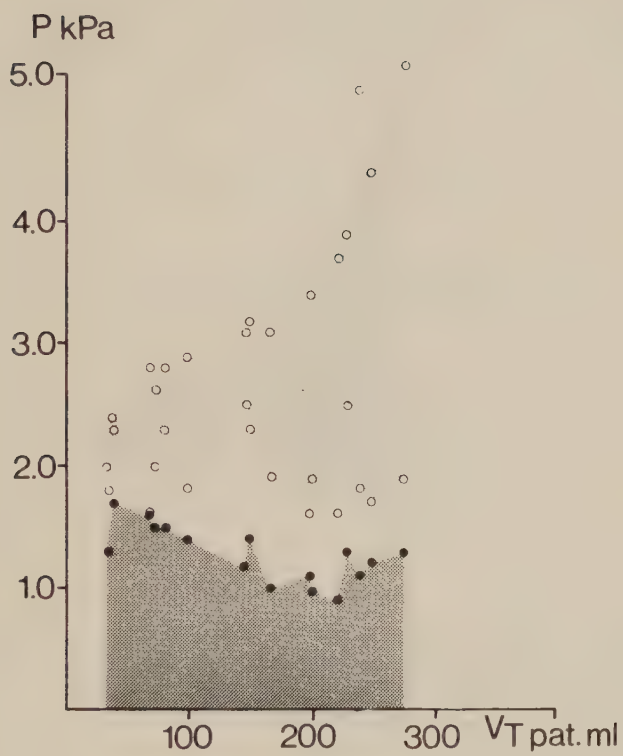


Fig. 3. b. Corresponding data at 20 cycles/minute.

P_{peak} ($f = 15$) was 2.5 ± 0.11 kPa and at $f = 20$ cycles/minute, 2.0 ± 0.08 kPa.

P_{ei} ($f = 15$) was 1.6 ± 0.07 kPa and at $f = 20$ cycles/minute, 1.3 ± 0.06 . The difference between pressures recorded at $f = 15$ and 20 was significant ($p < 0.001$). In order to deliver adequate tidal volumes to the older children, the pressure in the ventilator's pressure chamber was substantially increased at both frequencies. However, the increased chamber pressure (P_{vent}) did not influence P_{peak} or P_{ei} (Fig. 3 a, b).

Dynamics of insufflation

The duration of insufflation was 0.64 ± 0.02 s at $f = 15$ and 0.58 ± 0.02 s at $f = 20$ cycles/minute (Table 2).

A rectilinear relationship was recorded between the simultaneous volume and pressure changes during insufflation (Fig. 4). The slope was of the same magnitude for both ventilatory frequencies.

Total compliance

A rectilinear relationship was established between C_{TOT} and kg b.w. The regression equation was $C_{\text{TOT}} = 11.2 \cdot \text{kg b.w.} - 12.5$. The coefficient of correlation was 0.95.

Before surgery the average total compliance of the patients was 143.5 ± 21.3 ml/kPa. This value decreased to 122.5 ± 18.1 ml/kPa ($p < 0.01$) at the end of the initial stage of the surgical procedure (Table 3). When the ventilatory frequency was lowered the compliance value remained unchanged.

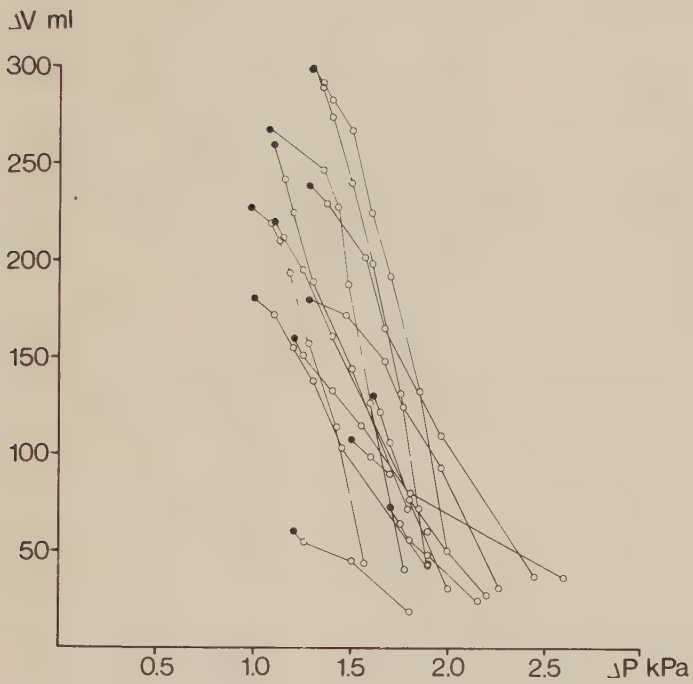


Fig. 4. Volume/pressure relationships (open circles) during insufflation in children of different body weights. Filled circles represent the end-tidal tracheal pressure.

TABLE 3. Total compliance before and during surgery in all 16 cases.

Pat. No.	C_{TOT}	ml/kPa
	Before surgery	During surgery
1	174.6	182.3
2	54.7	42.5
3	213.3	200
4	118.5	97.3
5	208	180
6	51.4	42.5
7	246.7	220
8	72.3	61.3
9	252.7	194.3
10	57.1	50.0
11	28.0	22.4
12	216.4	188.3
13	30	26.2
14	255	180
15	191.1	160
16	125.5	113.3
M	143.5	122.5
S.E.	21.3	18.1
Sign.	$p < 0.01$	

DISCUSSION

The need for ventilatory standards in controlled ventilation is particularly felt during anaesthesia and surgery in children. In the treatment of various types of neonatal respiratory insufficiency as well as in the postoperative period, ventilatory standards ensure a practical setting procedure and may in addition serve as an important prognostic tool.

The recommended tidal volume for infants at the ventilatory frequency of 20 cycles/minute, as calculated from RADFORD et al's nomogram (1954), amount to 7 - 8 ml/kg b.w. OKMIAN (1963) based his nomogram for the Engström respirator upon RADFORD's standards. He introduced the standard frequency of 20 cycles/minute and added corrections for gas compression. In order to achieve safe hyperventilation during surgery, OKMIAN et al (1966 a) recommended tidal volumes of a magnitude of 10 ± 2 ml/kg b.w. and reported good results.

ENGSTRÖM et al (1962) modified a nomogram for adults (ENGSTRÖM & HERZOG 1959) to suit infants. They used the alveolar ventilation formula to obtain a "basal alveolar ventilation". The values for the 24 hour caloric metabolism were obtained from tables published by BENEDICT & TALBOT (1921). For the sake of conformity with the adult nomogram the authors multiplied their basal values by a correction factor of 1.3. The dead-space of the patient in litres was calculated as being 5 % of the body surface area in square meters and the gas compression within the respirator and tubing as being 60 ml/respiratory cycle. To the best of our knowledge no clinical material has been reported hitherto, confirming the validity of this nomogram.

Thus, reported standards for artificial ventilation in infancy diverge substantially in several respects. On the other hand a certain conformity exists, surprising when one considers the different methods used. We have chosen four cases from our series covering the range of body size between 5 and 20 kg, to reveal some important differences in the recommended minute volumes (Fig. 5). Primarily, our measured ventilatory volumes were some-

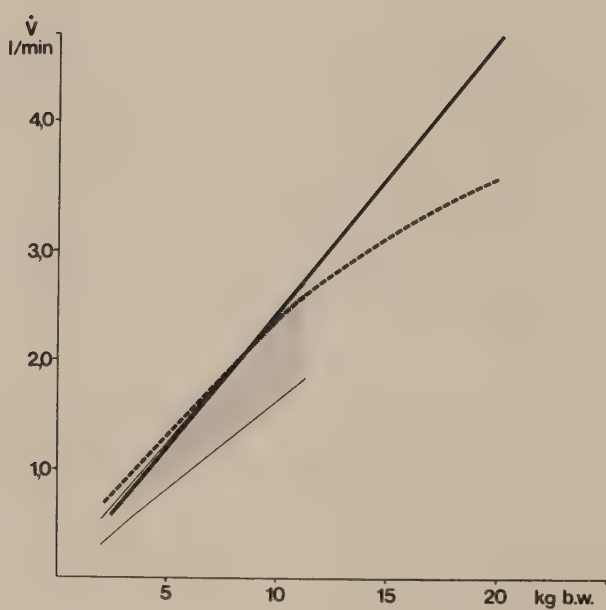


Fig. 5. Suggested pulmonary ventilation ENGSTRÖM et al nomogram (broken line), OKMIAN et al (shaded area). Recorded data in our series (continuous line) at $f = 20$.

what larger than those recorded by OKMIAN et al (1966 a). The divergence of minute volume between our series and ENGSTRÖM et al's calculations increased with increasing body weight (Fig. 5). Besides, the agreement between values for minute volume in the 5 to 10 kg b.w. range is false, as different frequencies are involved.

Thus the correlation between ventilatory volume, dead-space volume and different parameters for body size are of particular interest. We found that the recorded tidal volumes correlated linearly to kg b.w. at $f = 20$ as well as at $f = 15$ cycles/minute. The regression equation for $f = 20$ indicated that tidal volume was almost directly proportional to kg b.w. Tidal volumes calculated by means of the average value 12.1 ml/kg diverged maximally $\pm 4\%$ from the values obtained by the regression equation within the range 2.5 to 22.5 kg b.w. On the other hand the regression equation for $f = 15$ showed no direct relationship to kg b.w., especially for the lower body weights. The tidal volume at 2.5 kg b.w., for instance, calculated according to the average value 15.9 ml/kg is underestimated by 24% in proportion to that calculated according to the regression equation.

The high degree of correlation found between tidal volume and kg b.w. is in agreement with OKMIAN et al (1966b) but surprisingly, tidal volumes also correlated extremely well to body surface area in square meters, calculated by the DuBOIS & DuBOIS' formula (1916), and a clear cut linear regression was demonstrated ($r = 0.997$, $\text{kg} = 28.3 \text{ m}^2 - 3.0$). To test whether or not these correlations depended upon a degree of selection in our series, heights and b.w. from 116 healthy children between 3 and 20 kg, were collected and the relationship between b.w. and body surface area was investigated. The calculated regression equation was $\text{m}^2 = 0.0362 \text{ kg b.w.} + 0.09$ and the coefficient of correlation 0.996. The investigation will be published elsewhere (OKMIAN et al 1977).

ENGSTRÖM et al (1962) scrutinized RADFORD's standards. In their opinion the dead-space values employed by RADFORD, 2 ml/kg b.w., were too low and besides, they believed that body sur-

face area as a reference for human biological data, rather than body weight generally gives better correlation. However, we have calculated the dead-space values according to ENGSTRÖM et al's recommendations using the data of all the children in our series. We found the average value to be 2.2 ml/kg b.w. and a standard deviation of 0.22 (regression equation $V_D = 1.8 \cdot \text{kg b.w.} + 5.2$, $r = 0.999$). Obviously no importance can be attached to the slight difference between ENGSTRÖM et al's hypothetical values of dead-space volume and RADFORD et al's calculations.

The difference between our measured pulmonary ventilation and ENGSTRÖM et al's calculated volumes, especially between 10 and 20 kg b.w. should to a large extent be related to the authors' opinion of body surface as a reference for dead-space calculations. This is true since the scale for alveolar ventilation in their nomogram is a metric one and the deviation of their values from our ventilatory values is exponential (Fig. 5). Besides it is a well known fact that the ratio of body surface area in square metres to kg b.w. decreases with increasing age. When for instance, V_D for 3 kg b.w. and 20 kg b.w. are compared, calculated according to the above regression equation the ratio V_D/kg is 170% larger at 3 kg than at 20 kg b.w. The too high V_D calculated from ENGSTRÖM et al's nomogram using the higher ventilatory frequencies for neonates, increases the recommended volume of pulmonary ventilation in patients with body weights below 10 kg.

In our series as well as in OKMIAN et al's (1966 a) a linear relationship was shown to exist between total compliance and b.w. In OKMIAN et al's investigation the tidal volumes used resulted in a mean capillary CO_2 tension of 35 mm Hg, i.e. 4.7 kPa. In our investigation, the hyperventilation was more pronounced (an arterial CO_2 tension of 3.7 kPa) at the same ventilatory frequency ($f = 20$ cycles/minute). This could partly explain the difference in tidal volumes. Another and reasonable explanation for the discrepancy in pulmonary ventilation could be that the Engström respirator used by OKMIAN et al did not terminate the insufflation within the available time for inspiration. This factor increased the end-inspiratory tracheal pressure (LINDAHL et al 1977 b). The mean values for end-inspi-

ratory pressures were also shown to be 0.35 kPa higher in the investigation by OKMIAN et al (1966 a) in spite of the larger tidal volumes used in our series at the same ventilatory frequency. OKMIAN et al's series also included a few neonates with pulmonary diseases and furthermore they used a spring loaded valve with opening pressures of 0.1 to 0.2 kPa. The net effect of these differences was certainly reflected in the divergencies in total compliance, which was shown to be 8.9 ± 1.8 ml/kPa/kg b.w. by OKMIAN et al (1966 a) and 9.7 ± 0.54 ml/kPa/kg b.w. in the present study. In our series total compliance was significantly reduced during the initial part of the surgical procedure in accordance with OKMIAN et al's and NORLANDER et al's (1968) results. The change of ventilatory setting from $f = 20$ and 33 % inspiration time to $f = 15$ and 20 % inspiration time, did not influence total compliance.

The ventilatory frequency of 15 cycles/minute demanded tidal volumes of 15.9 ± 1.5 ml/kg b.w. to keep the ventilatory level unchanged ($P_a\text{CO}_2$ 3.9 kPa) and maintain end-inspiratory tracheal pressures at 1.6 ± 0.07 kPa. This pressure level is well below the margin for pulmonary damage set by OVENFORS (1964). Thus, ventilatory frequencies of about 1/2 those of spontaneous breathing could be employed, to the benefit of less dead-space ventilation per minute (LINDAHL et al 1977 c) and perhaps also for the surgeon. Experimental data have also revealed that a low ventilatory frequency brought about a high cardiac output, and low pulmonary and systemic vascular resistances. Prerequisite conditions were the existence of static end-inspiratory tracheal pressure and a short insufflation time, prolonging the time of exhalation (LINDAHL et al 1977 d). Consequently $P_a\text{O}_2$ levels recorded at $f = 15$ in this investigation were higher than at $f = 20$.

The endo-tracheal peak pressure maintained a fairly constant pressure level which was independent of the initial pressure within the ventilator, the tidal volume and the body weight (Fig. 3 a, b). This unexpected phenomenon could be explained by the hypothesis that the proportional increase in total lung volume and functional residual capacity in the older children compensated for the higher pressures within the ventilator pressure chamber, when large tidal volumes were administered.

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